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An uncertain future for the climate and health impacts of anthropogenic aerosols in Africa

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African regional groupings in **Figure 1** are adapted from the World Health Organization (WHO) classifications, with minor adjustments to include all continental countries. Specifically, Sudan, South Sudan, and Somalia were reclassified from the WHO Eastern Mediterranean Region to Eastern Africa, and Libya, Egypt, Tunisia, Morocco, and Western Sahara were reclassified to Northern Africa. These countries are considered part of the Eastern Mediterranean Region in the original WHO classifications but are geographically part of the African continent.

Table S1: Summary of emission scenarios and their characteristics

Scenario Group	Scenario Name	Shorthand	Characteristics
SSPs (Riahi et al., 2017)	SSP1-1.9	SSP119	Sustainability pathway - rigorous air pollution control, low climate forcing, and minimal challenges in mitigation and adaptation
	SSP2-4.5	SSP245	Middle-of-the-road pathway - moderate air pollution control, moderate climate forcing, moderate mitigation and adaptation challenges
	SSP3-7.0	SSP370	Regional rivalry - weak air pollution control, high climate forcing, significant challenges in both mitigation and adaptation.
	SSP5-8.5	SSP585	Fossil-fueled development - very high climate forcing, strong air pollution control high socio-economic challenges for mitigation and low socio-economic challenges for adaptation
ECLIPSE (IIASA, 2023)	Current Legislation	ECL6 CLE	Continuation of current legislation and existing regulatory frameworks.
	Maximum Feasible Reduction	ECL6 MFR	Air pollution reductions through the implementation of advanced technologies and practices
	Sustainable Development Scenario	ECL6 SDS	Targeted air pollution reductions for SDGs
UNEP (UNEP, 2022)	Baseline	UNEP BASE	Business-as-usual trajectory for Africa
	Short-Lived Climate Pollutants	UNEP SLCP	Focus on SLCP mitigation (black carbon, methane, and hydrofluorocarbons)
	Agenda 2063	UNEP 2063	Ambitious scenario aligned with long-term African sustainability goals

We conducted a comparison of the OsloCTM3 driven by CEDS21 anthropogenic emissions against $PM_{2.5}$ Surface Observations in 2019 from reference monitors at U.S. embassy locations in Africa and satellite-derived $PM_{2.5}$ from combined AOD retrievals from the NASA MODIS, MISR, and SeaWIFS with the GEOS-Chem model (**Figure S1**). These comparisons can be challenging for several reasons including coarse model spatial resolution and meteorological year consistency with measurement year, and thus should not be over-interpreted but instead viewed as a "sanity check". The OsloCTM3 model broadly captures the seasonal cycle better in west Africa than in east Africa. This is also evident in the R^2, RMSE, and MAE (**Table S2**). $PM_{2.5}$ levels in West Africa are heavily influenced by Harmattan winds that carry dust from the Sahara Desert (Amooli et al., 2024; Anuforom, 2007; Bahino et al., 2024), such that accurate $PM_{2.5}$ simulation in a model heavily relies on how well it represents atmospheric circulation.

However, $PM_{2.5}$ concentrations in East Africa are more heavily influenced by local emissions (Kalisa et al., 2023) and thus the accuracy of model climatologies depends largely on the precision of emissions inventories. Another reason could be the simplicity of the seasonal cycles. West Africa experiences only two distinct seasons: the rainy season and the dry season. However, East Africa's rainfall patterns are generally more variable due to complex large-scale processes, resulting in boreal summer, spring, and autumn seasons (Nicholson, 2017). The model underestimates surface $PM_{2.5}$ observations in Kampala and Kigali, and overestimates in Dakar. The OsloCTM3 model at its native 2.25° latitude by 2.25° longitude resolution performs best in Accra, Ouagadougou, Abidjan, Abuja, Cairo, and N'Djamena with ranging from 0.48 to 0.76 and MAE ranging from 5.7 $\mu g\ m^{-3}$ to 23.8 $\mu g\ m^{-3}$. The model performs worst in Kampala, Nairobi, Kigali, Addis Ababa, and Dakar, with R^2 ranging from 0.002 to 0.39. The satellite $PM_{2.5}$ agrees well with surface observations in Accra, Ouagadougou, Abidjan, Addis Ababa, and N'Djamena with R^2 ranging from 0.84 to 0.93. The model and the satellite both agree in Accra, Ouagadougou, Abidjan, Addis Ababa, Kigali, and N'Djamena with R^2 ranging from 0.43 to 0.72 and MAE ranging from 3.2 $\mu g\ m^{-3}$ to 13.3 $\mu g\ m^{-3}$. The downscaled resolutions perform similarly to the native resolution, with performance metrics of the same order of magnitude, though slightly better over Africa overall. However, at the city level, performance varies by location.

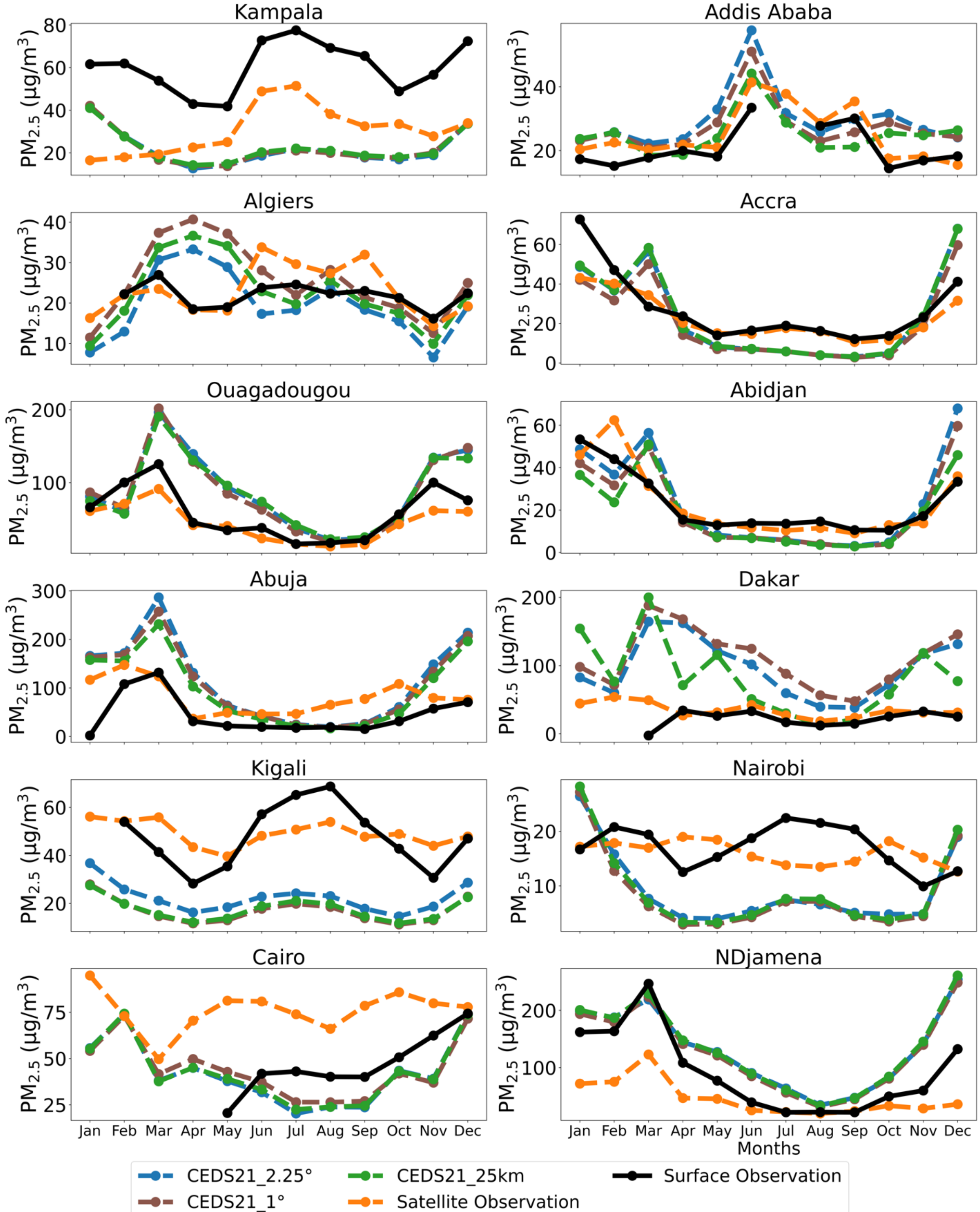

Figure S1: Evaluation of OsloCTM3 driven by CEDS21 anthropogenic emissions against $PM_{2.5}$ Surface Observations in 2019

Table S2: Evaluation of OsloCTM3 (native 2.25° latitude by 2.25° longitude resolution) and satellite-derived $PM_{2.5}$ against surface observations in 2019

U.S. Embassy Location	R^2			RMSE (µg m^{-3})			MAE (µg m^{-3})		
	model	satellite	model vs satellite	model	satellite	model vs satellite	model	satellite	model vs satellite
Kampala	0.20	0.41	0.05	10.01	8.67	10.64	8.91	7.06	8.98
Addis Ababa	0.39	0.88	0.53	4.79	2.15	5.26	3.64	1.55	3.98
Algiers	0.09	0.03	0.02	2.75	2.85	6.19	2.17	2.29	5.36
Accra	0.55	0.84	0.72	11.58	6.81	5.73	7.53	4.29	4.29
Ouagadougou	0.53	0.93	0.59	23.89	9.73	15.30	19.64	7.74	12.33
Abidjan	0.66	0.87	0.55	8.06	5.03	10.98	5.74	3.44	6.89
Abuja	0.62	0.36	0.32	23.84	30.92	28.05	15.81	23.38	23.38
Dakar	0.01	0.03	0.09	10.94	10.79	10.66	9.17	9.01	9.17
Kigali	0.17	0.01	0.43	11.61	12.69	3.94	9.98	11.06	3.23
Nairobi	0.002	0.06	0.01	3.89	3.77	2.06	3.46	3.15	1.93
Cairo	0.48	0.20	0.06	10.87	13.49	11.90	8.94	11.80	9.74
N'Djamena	0.76	0.89	0.46	33.71	22.31	21.32	23.83	17.03	13.30
Africa-average	0.37	0.46	0.32	13.00	10.77	11.00	9.90	8.48	8.55

The modelled AOD for 2019 is compared with a 5-year (2017-2022, excluding Covid year 2020) average MODIS AOD (**Figure S2**), considering the substantial year-to-year variability in MODIS data, particularly after 2010 (Vogel et al., 2022). The R^2 value between the model and MODIS Aqua is 0.36, with RMSE and MAE of 0.11 and 0.08 respectively. This suggests that the model captures a modest portion of the variability in MODIS Aqua AOD, indicating potential limitations in the model's representation of factors influencing AOD.

The overall difference between OsloCTM3 and MODIS Aqua AOD is -6 %. A previous study by Lund et al. (2023) found that the OsloCTM3 simulated global mean AOD is approximately 20 % lower than that derived from MODIS Aqua. However, the study also noted that the model, with CEDS21 emissions, better captures observed global and regional trends compared to using CEDS emissions. Additionally, Lund et al. (2018) reported improved agreement between the OsloCTM3 model output and ground-based Aerosol Robotic Network (AERONET) observations for the year 2010.

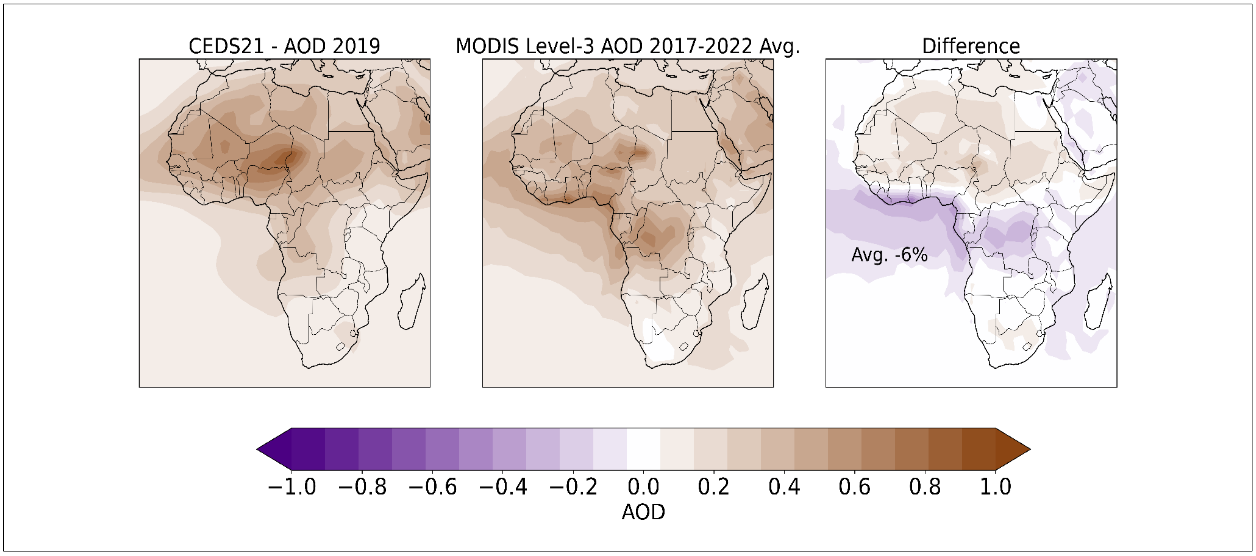

Figure S2: Evaluation of OsloCTM3 driven by CEDS21 anthropogenic emissions against MODIS Level-3 2017-2022 average AOD, excluding Covid year 2020.

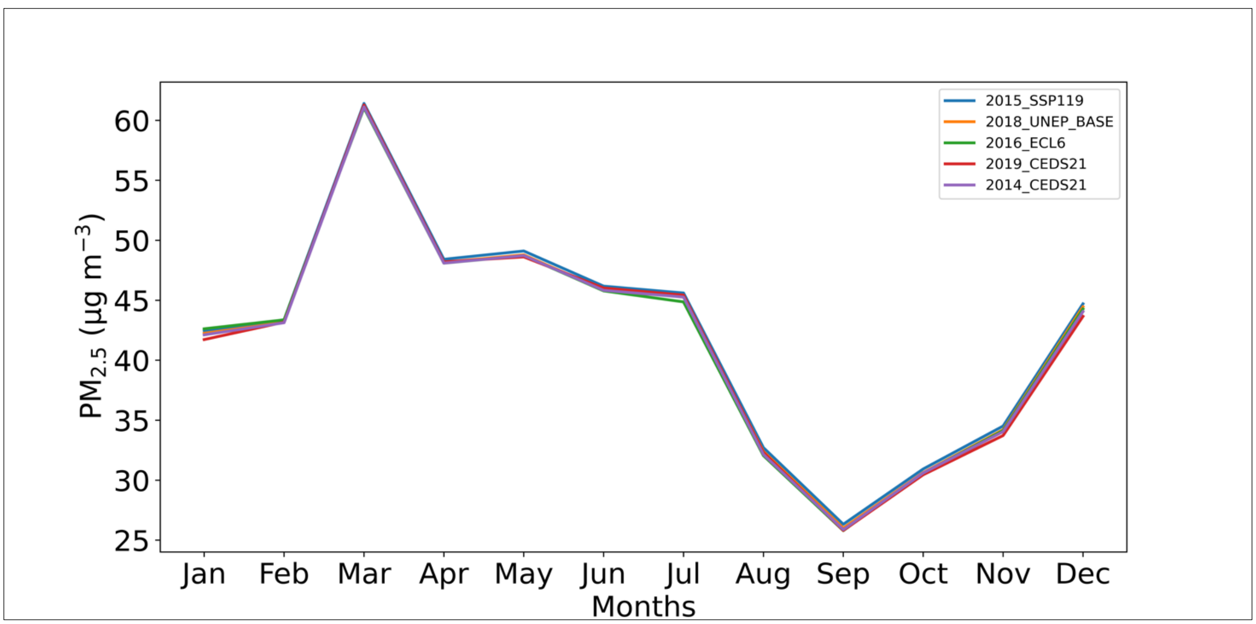

Figure S3: Comparison of Differences in Emission Inventories (2015-2018)

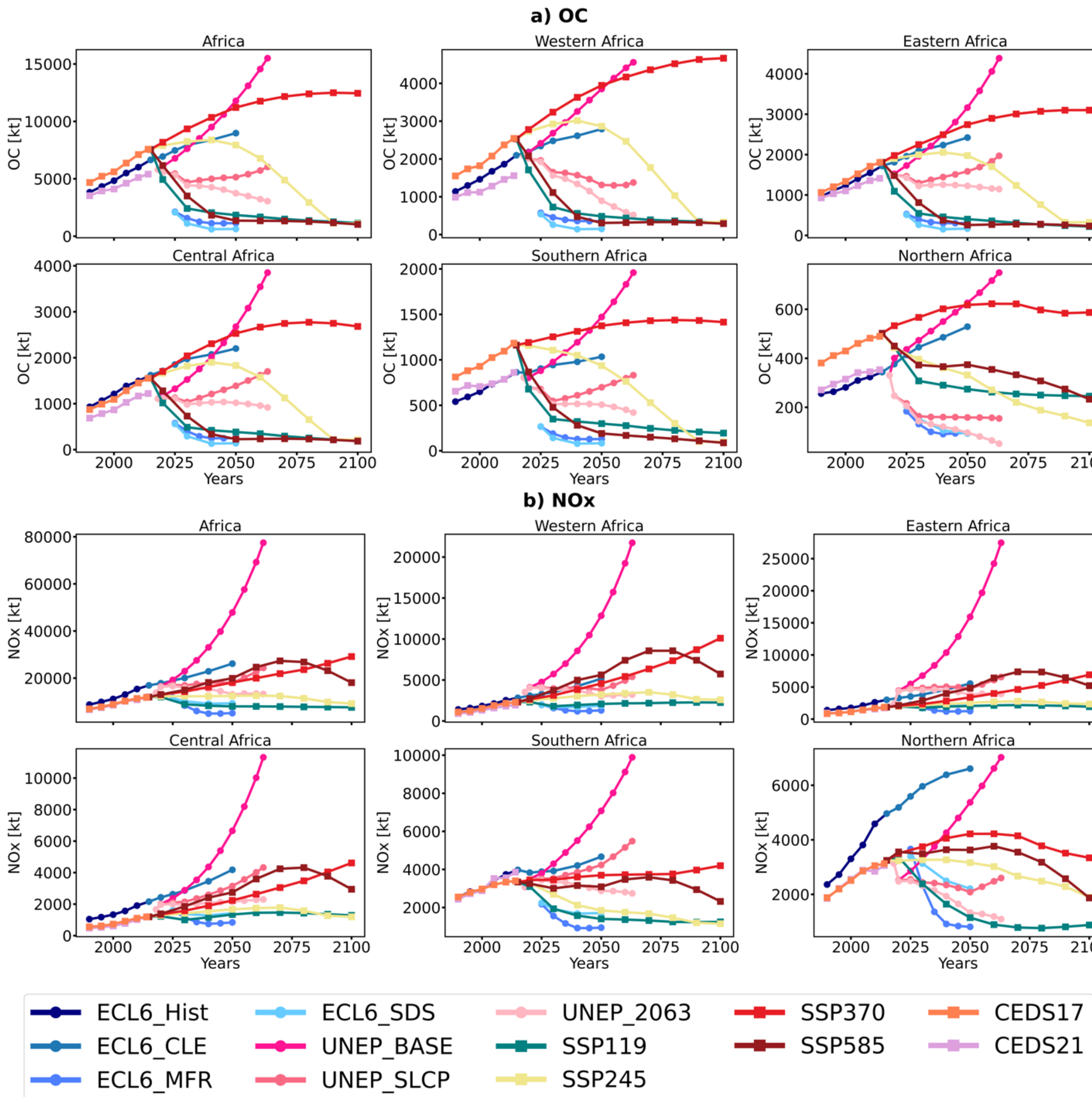

Figure S4: Large spread and regional heterogeneity in projected air pollution emissions in sub-Saharan Africa, shown for a) OC and b) NO_x. Note: The y-axis scales vary between regions. ECL6_Hist represents historical emissions from the ECLIPSE Version 6b inventory. CEDS17 and CEDS21 represent historical emissions from the CEDS versions 2017 and 2021, respectively.

BC emissions are projected to increase under SSP245 in Western, Central, and Eastern Africa, driven by the residential, transportation, and industrial sectors (**Figure S6)**. However, BC emissions are expected to decrease under SSP119, driven by reductions in the residential, energy, waste, and transportation sectors. Under ECL6 SDS, BC emissions are projected to decrease across most regions, driven by reductions in the residential, transportation, and agriculture sectors, except in Southern Africa, where emissions will be driven by the residential, transportation, and industrial sectors. BC emissions are also projected to decrease under UNEP SLCP (in Western, Eastern, and Northern Africa) due to reductions in the residential, energy, industrial, and waste sectors, and under UNEP 2063, driven by reductions in the residential, energy, industrial, waste, and agriculture sectors.

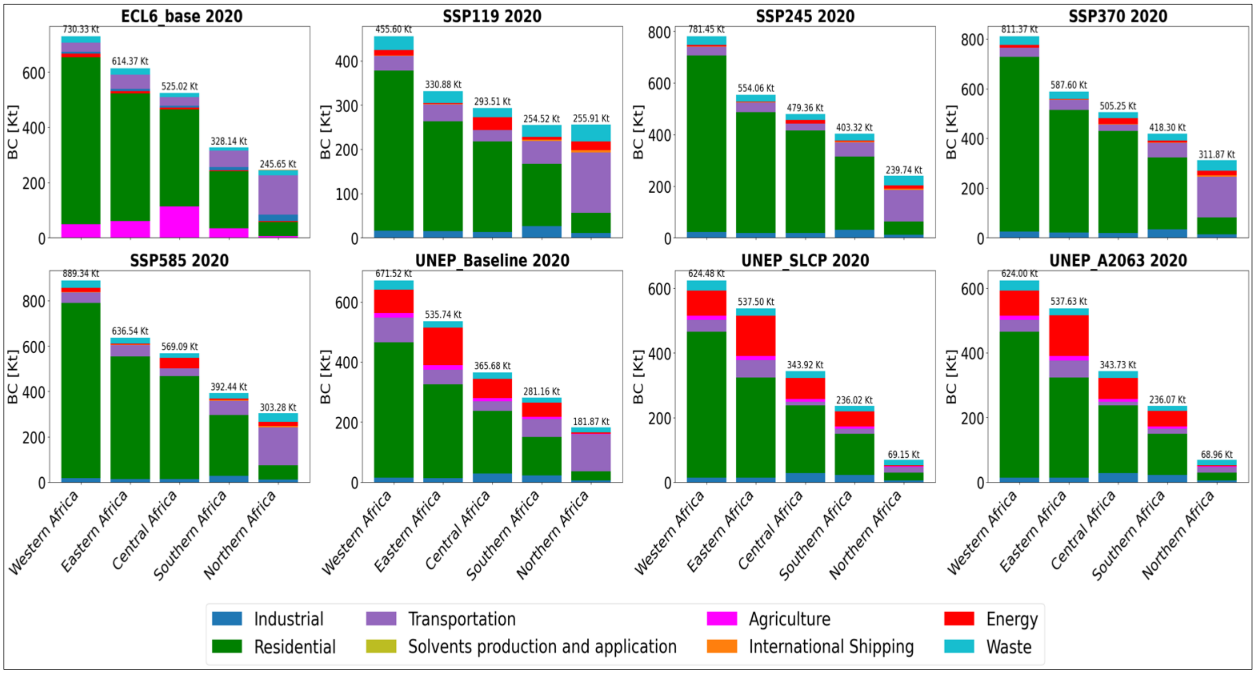

Figure S5: Sectoral Contributions to BC in 2020 across all scenarios. ECL6 MFR and ECL6 SDS start with ECL6 baseline

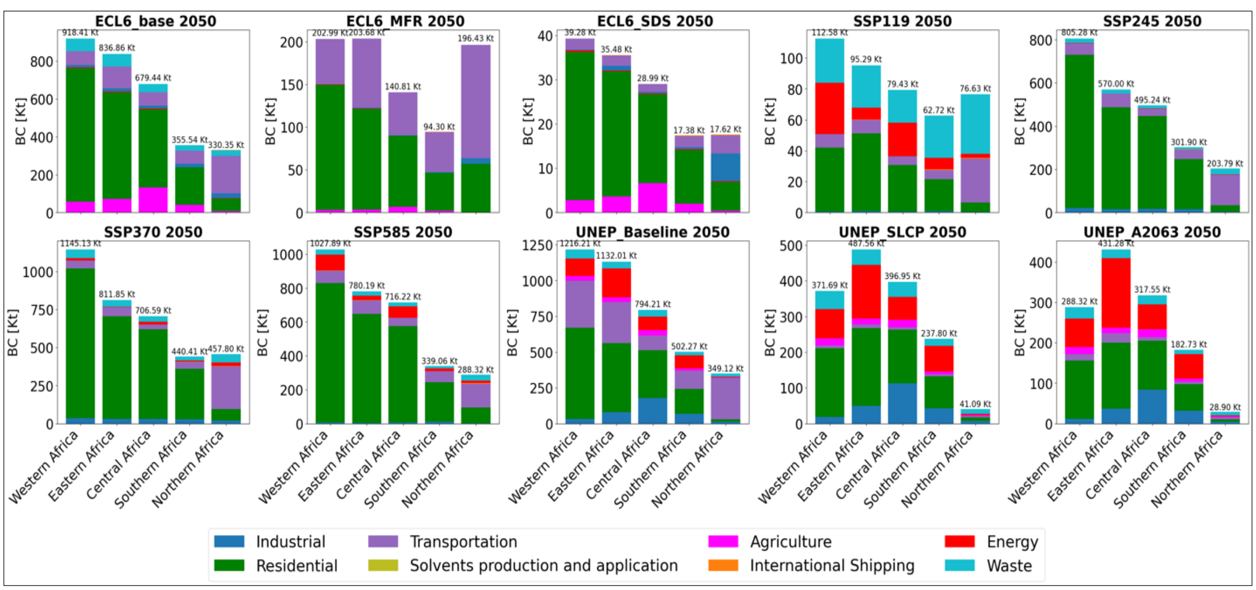

Figure S6: Sectoral Contributions to BC in 2050 across all scenarios

SO_2 emissions are projected to increase across all sub-regions by 2050 under the UNEP SLCP and UNEP 2063 scenarios, driven by the industrial and energy sectors (**Figure S8**). Additionally, SO_2 emissions are projected to increase under SSP119 (except in Western and Northern Africa) and SSP245 (except in Southern and Northern Africa), largely driven by the industrial sector. Under the ECL6 SDS and ECL6 MFR scenarios, SO_2 emissions are projected to slightly increase by 2050, driven by emissions from the industrial, energy, and transportation sectors.

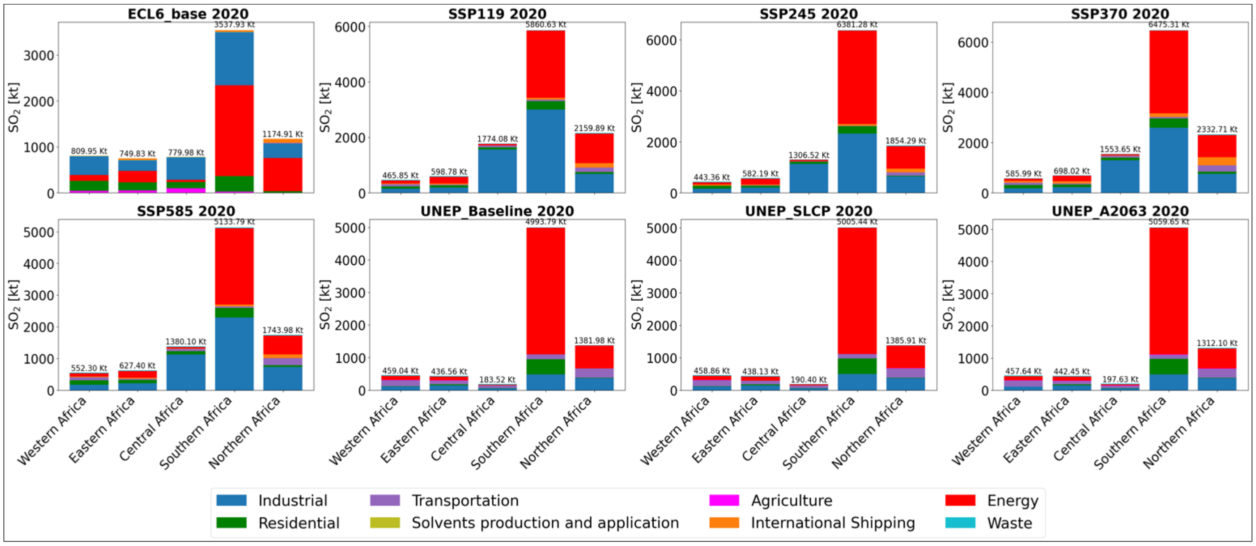

Figure S7: Sectoral Contributions to SO_2 in 2020 across all scenarios, ECL6 MFR and ECL6 SDS start with ECL6 baseline

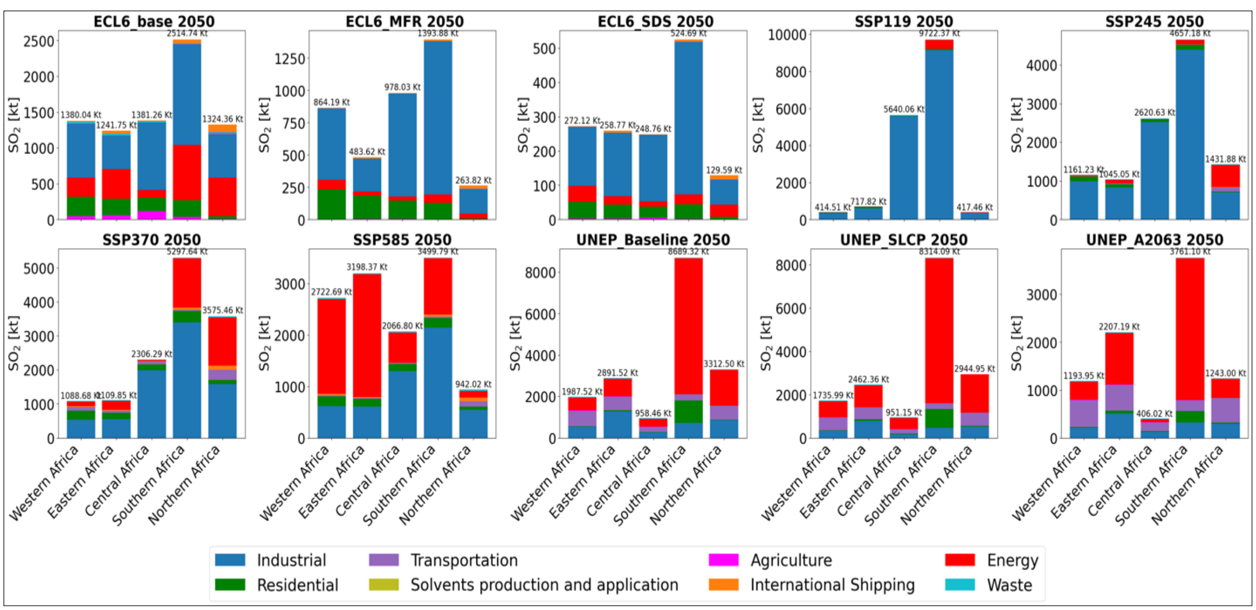

Figure S8: Sectoral Contributions to SO_2 in 2050 across all scenarios

The residential sector is the dominant contributor of OC emissions in both 2020 and 2050 in sub-Saharan Africa under the SSPs, UNEP, and ECL6. Under the SSPs, the residential sector is followed by waste; under the UNEP, it is followed by waste, energy, transportation, and agricultural waste burning on fields; and under ECL6, it is followed by agricultural waste burning on fields and waste (**Figure S9**). Similarly, the transportation sector is the dominant contributor to NOx emissions in both 2020 and 2050 in sub-Saharan Africa under both the UNEP and SSP scenarios, while the residential sector is the largest contributor under the ECL6 CLE scenario (**Figure S10**). Notably, the international shipping sector contributes significantly under the SSPs but is muted in the UNEP Baseline and ECL6 scenarios.

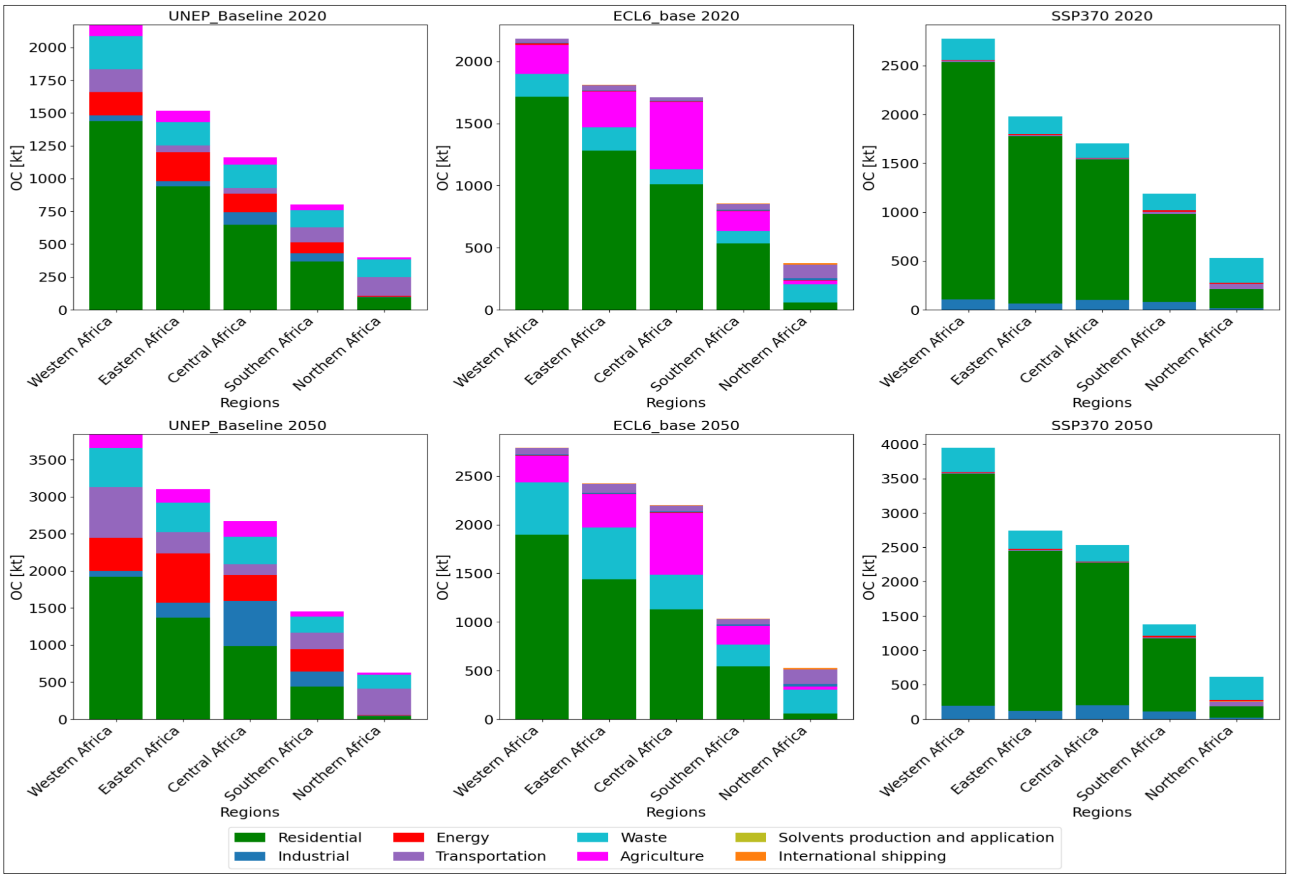

Figure S9: Sectoral Contributions to OC in 2020 (upper panel) and 2050 (lower panel) across increasing scenarios

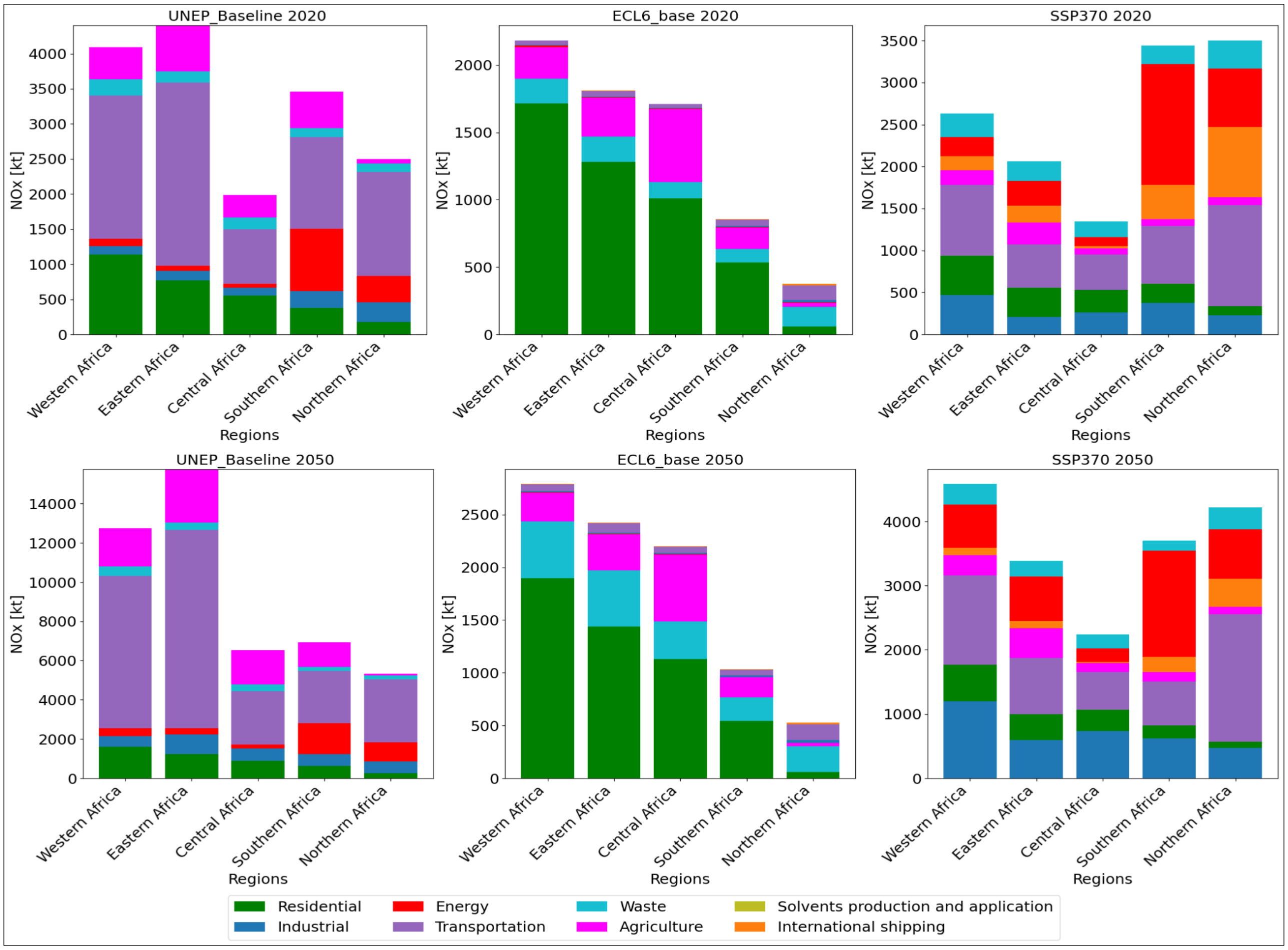

Figure S10: Sectoral Contributions to NO_x in 2020 (upper panel) and 2050 (lower panel) across increasing scenarios

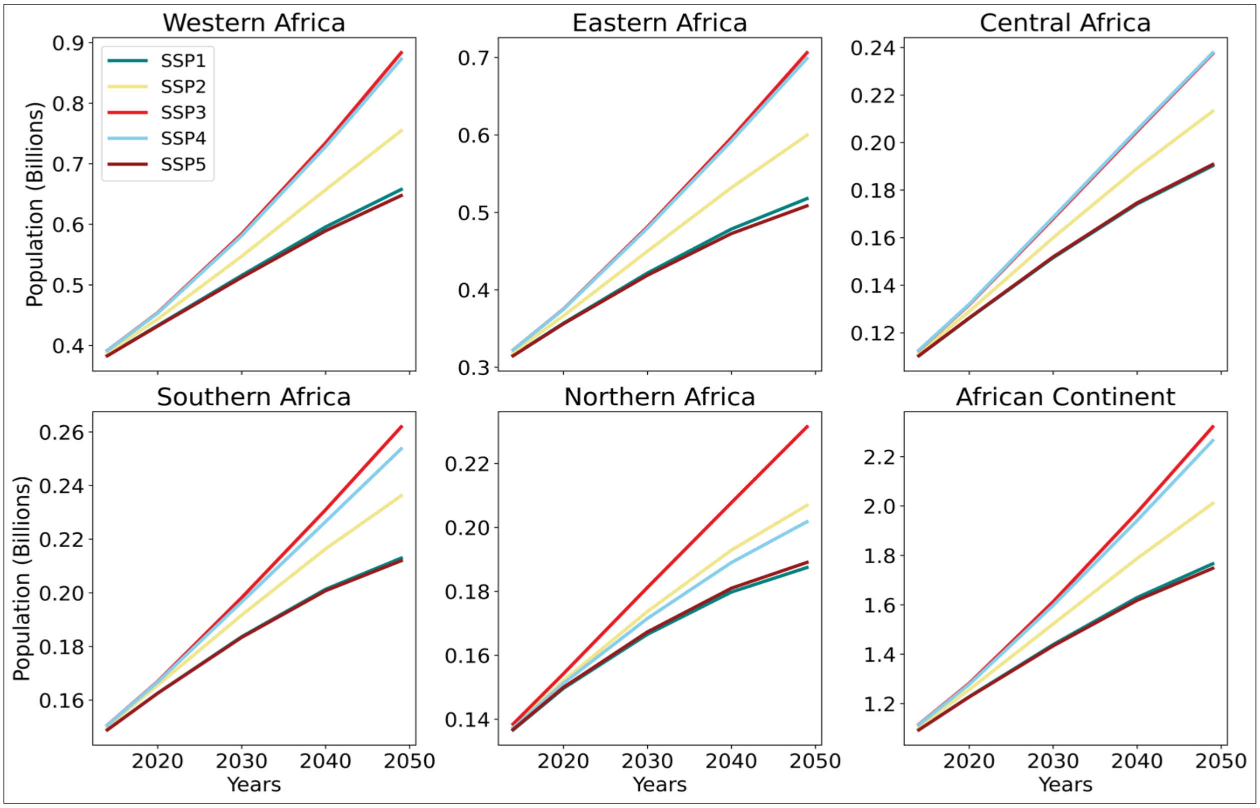

Figure S11: Population change by region and scenario between 2014 and 2050.

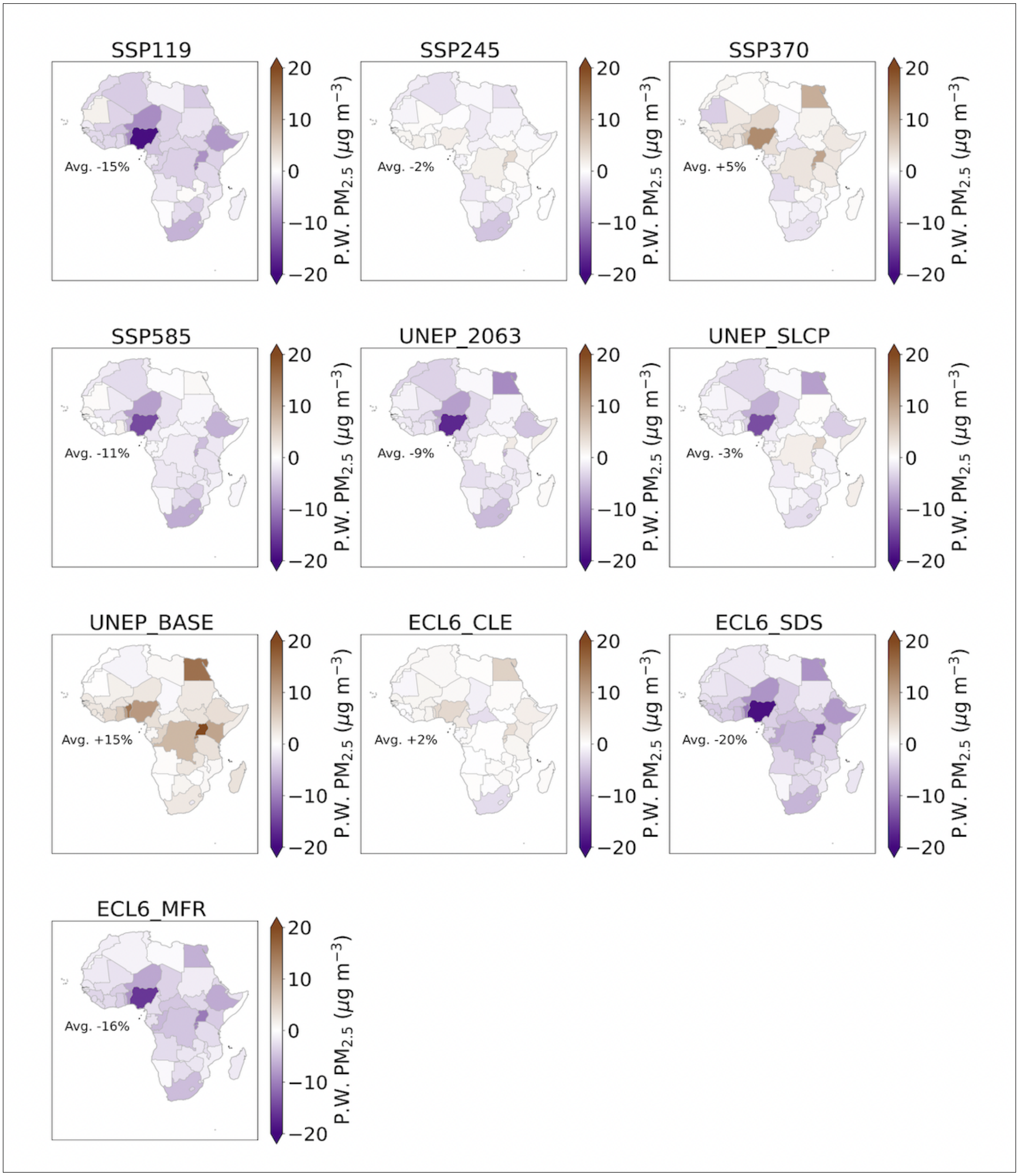

Figure S12: Difference in population-weighted $PM_{2.5}$ between 2015-2018 and 2050 across all scenarios

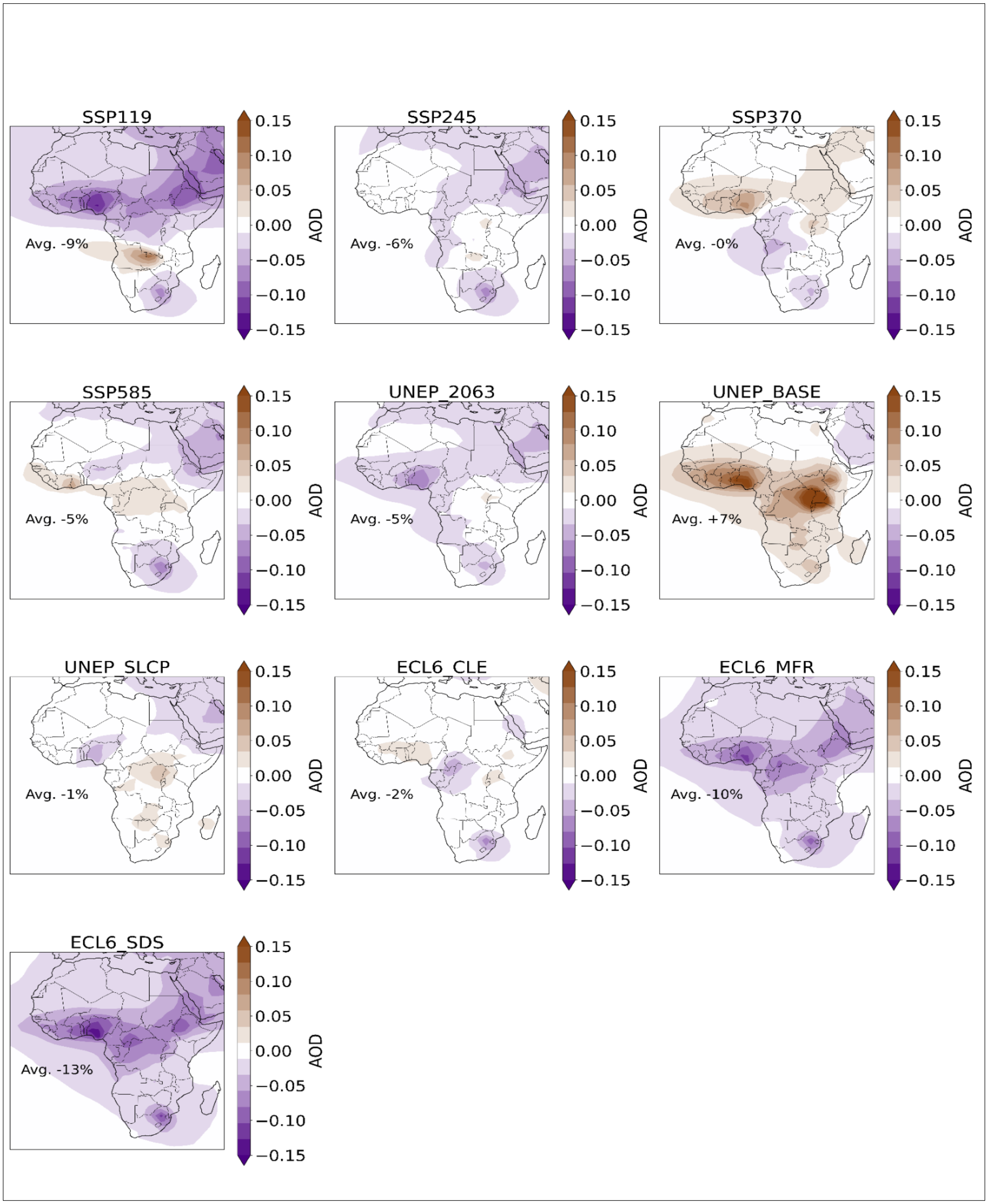

Figure S13: Difference in AOD between 2015-2018 and 2050 across all scenarios

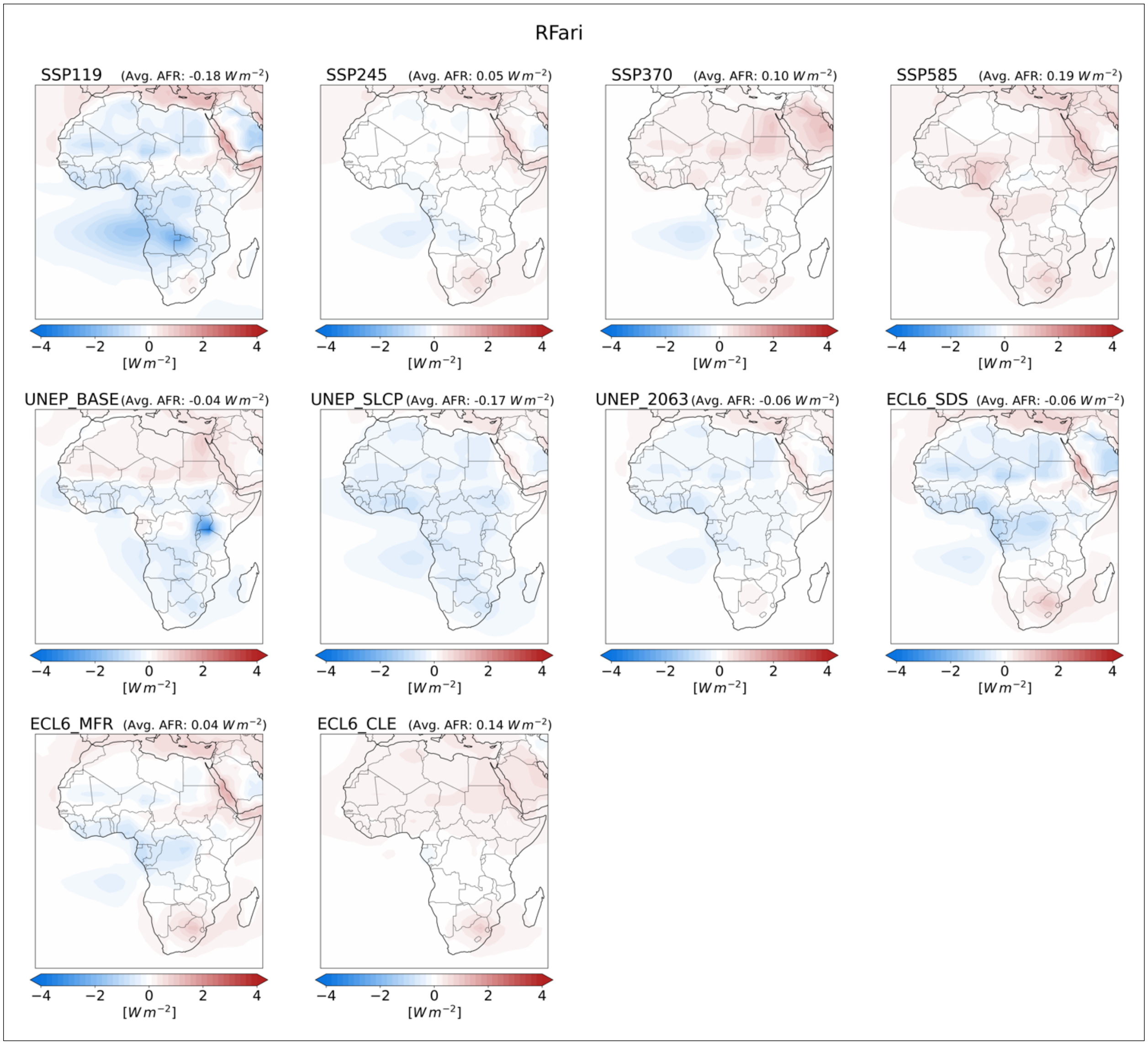

Figure S14: Radiative forcing from aerosol-radiation interactions due to changes in emissions between 2015-2018 and 2050.

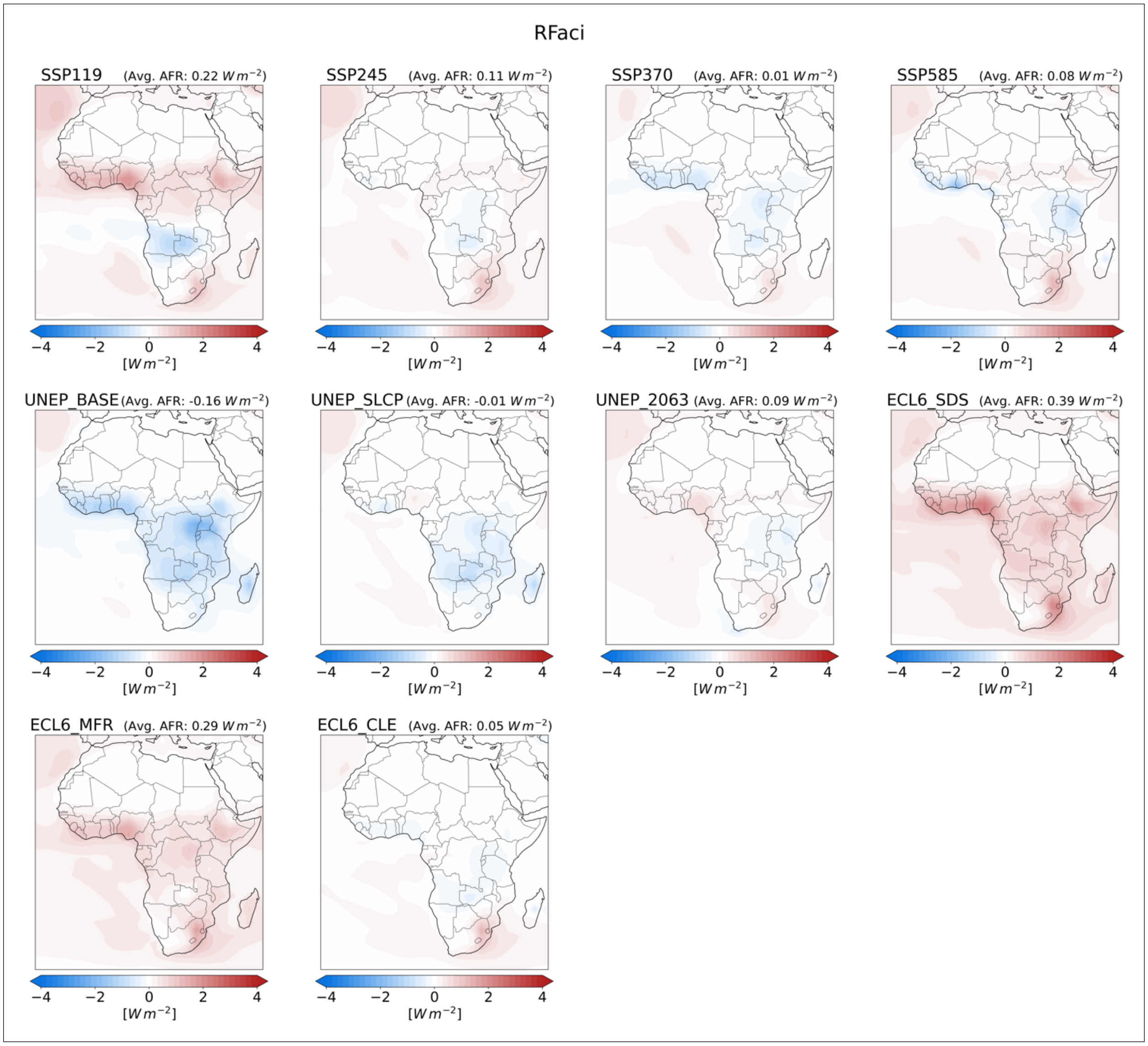

Figure S15: Radiative forcing from aerosol-cloud interactions due to changes in emissions between 2015-2018 and 2050.

Table S3: Regional changes in emissions, $PM_{2.5}$, excess deaths, and radiative forcing across scenarios between 2015-2018 and 2050

Region	Scenario	Emission (kt/yr)				Annual PM2.5 (μg m^{-3})	Excess deaths (in thousands)
		BC	SO2	OC	NO_x		
Africa	SSP585	733	1089	-6202	7961	-2.48	455
	SSP370	1143	2038	3654	6166	1.89	835
	SSP245	42	424	384	495	-0.28	710
	SSP119	-1992	5572	-5715	-3943	-3.95	370
	ECL6 CLE	865	-3150	2330	9228	0.82	705
	ECL6 MFR	-1446	-7011	-5507	-11785	-3.60	595
	ECL6 SDS	-2146	-9561	-6015	-7598	-4.54	575
	UNEP BASE	2116	10550	5991	34082	3.64	815
	UNEP SLCP	-343	9095	-656	4174	-1.50	665
	UNEP 2063	-629	1498	-2054	-680	-2.66	642
Western Africa	SSP585	294	2208	-2224	3311	-2.36	130
	SSP370	412	574	1416	2267	2.83	310
	SSP245	72	646	334	915	0.42	275
	SSP119	-621	-101	-2048	-233	-4.71	130
	ECL6 CLE	230	498	694	2338	1.07	270
	ECL6 MFR	-492	-19	-1742	-1527	-4.32	250
	ECL6 SDS	-655	-611	-1948	-945	-5.41	245
	UNEP BASE	592	1580	1763	9308	4.33	305
	UNEP SLCP	-252	1328	-777	252	-2.19	255
	UNEP 2063	-336	786	-1195	-539	-3.30	250
Eastern Africa	SSP585	246	2561	-1553	2969	-2.69	120
	SSP370	277	472	933	1524	2.86	280
	SSP245	35	408	167	679	0.52	235
	SSP119	-439	80	-1408	178	-4.29	120
	ECL6 CLE	277	268	702	2531	1.21	240
	ECL6 MFR	-357	-490	-1412	-1757	-4.19	200
	ECL6 SDS	-525	-715	-1553	-896	-5.17	195

	UNEP BASE	669	2549	1700	13563	6.01	280
	UNEP SLCP	25	2120	121	2371	0.25	235
	UNEP 2063	-31	1865	-237	1419	-0.89	225
Central Africa	SSP585	251	666	-1325	1547	-2.75	85
	SSP370	242	906	977	1040	1.48	130
	SSP245	30	1220	279	474	-0.10	120
	SSP119	-385	4240	-1168	144	-4.44	80
	ECL6 CLE	197	427	579	2018	0.79	115
	ECL6 MFR	-351	22	-1371	-1319	-4.11	95
	ECL6 SDS	-463	-707	-1481	-739	-5.19	90
	UNEP BASE	455	811	1567	4997	2.16	130
	UNEP SLCP	58	803	280	1485	-1.92	115
	UNEP 2063	-21	258	-89	485	-3.29	110
Southern Africa	SSP585	-72	-3085	-972	-250	-3.07	5
	SSP370	30	-1287	213	359	–0.63	15
	SSP245	-109	-1927	-226	-1491	-1.66	10
	SSP119	-348	3138	-864	-1936	-2.74	5
	ECL6 CLE	26	-3897	170	693	-0.28	10
	ECL6 MFR	-236	-5018	-735	-3032	-2.44	0
	ECL6 SDS	-312	-5887	-782	-2266	-2.98	0
	UNEP BASE	220	3734	666	3992	1.09	20
	UNEP SLCP	-45	3340	-107	1140	-1.34	10
	UNEP 2063	-100	-1213	-298	-218	-2.71	7
Northern Africa	SSP585	13	-1261	-128	383	-1.05	35
	SSP370	183	1372	116	974	2.28	100
	SSP245	-71	-771	-170	-81	-1.54	70
	SSP119	-199	-1786	-228	-2097	-2.83	35
	ECL6 CLE	137	-445	185	1648	1.37	70
	ECL6 MFR	-10	-1507	-248	-4151	-2.00	50
	ECL6 SDS	-190	-1641	-251	-2751	-2.99	45
	UNEP BASE	180	1875	295	2222	3.03	80

	UNEP SLCP UNEP 2063	-129 -141	1504 -198	-172 -234	-1074 -1828	-1.31 -2.52	50 50