

1 **Supplementary information**

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3 **Evidence for the impact of climate change on primary producers in the**
4 **Southern Ocean**

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6 **Hayward**

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MEASO summary areas

A summary of the MEASO sectors, zones and areas (Constable et al., this issue) is given in Figure 1.

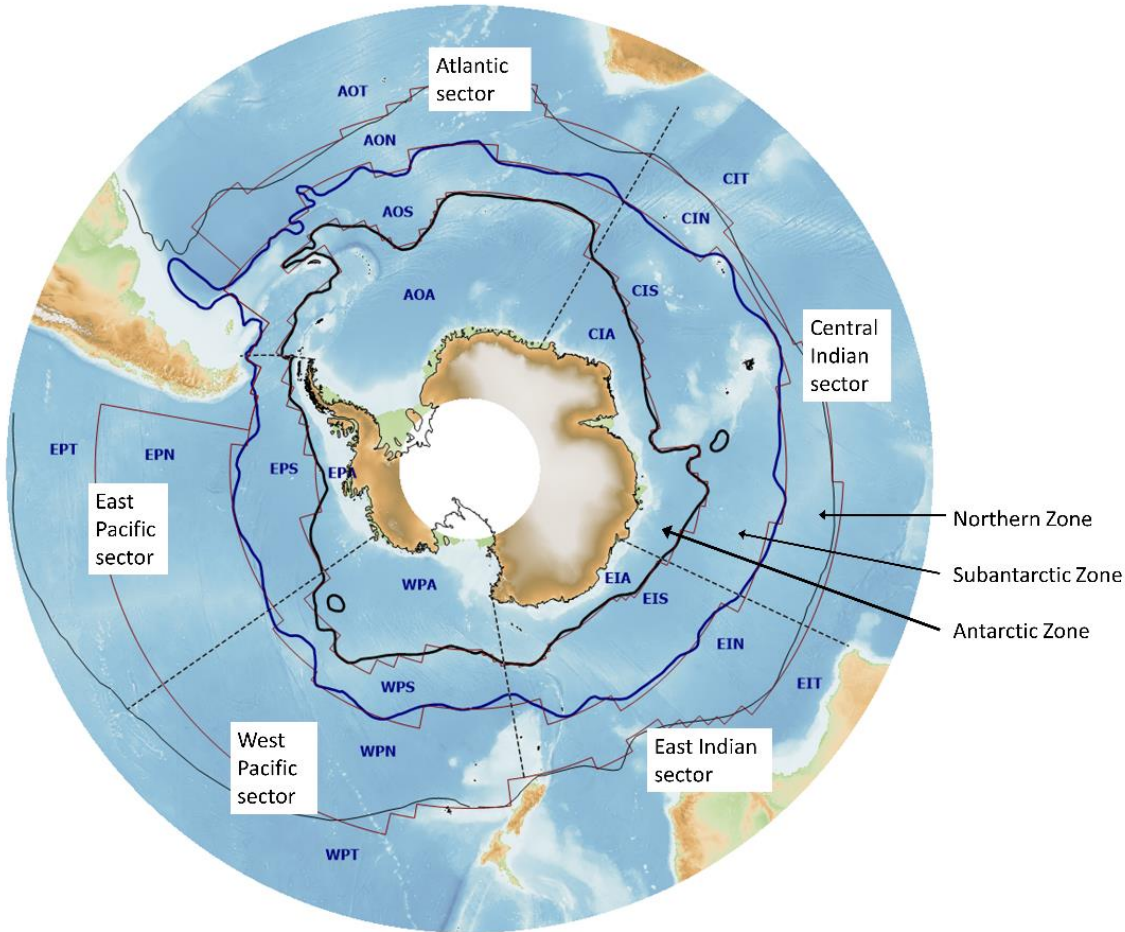
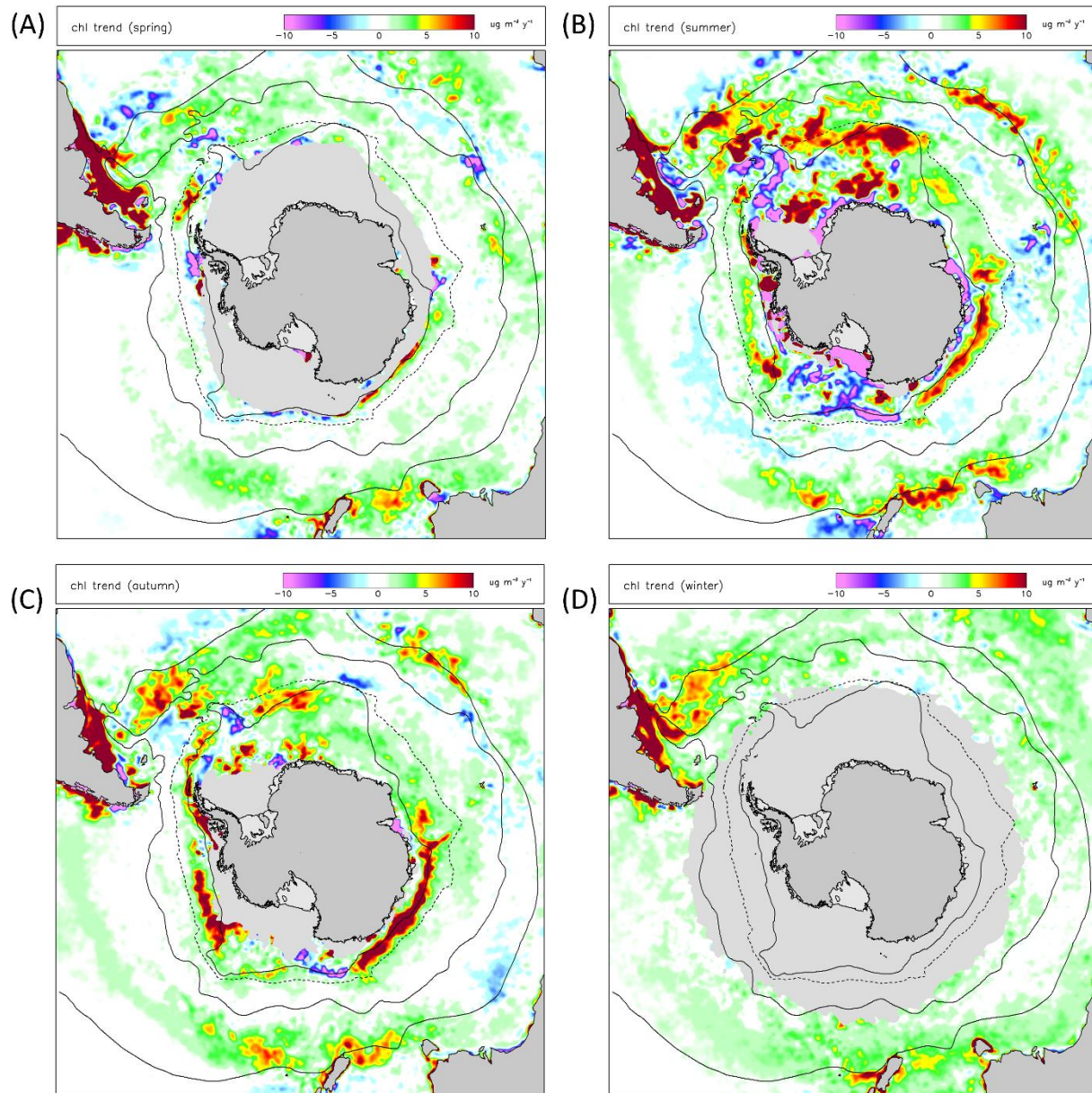


Figure 1. MEASO spatial descriptions has three parts: (1) Five longitudinal sectors: Atlantic, Central Indian, East Indian, West Pacific and East Pacific. (2) Three latitudinal zones: *Northern* (between Subtropical and Subantarctic fronts), *Subantarctic* (between Subantarctic and Southern Antarctic Circumpolar Current (ACC) fronts) and *Antarctic* (south of Southern ACC front). The Tropical zone (north of the Subtropical Front) is not used. There are 15 MEASO regions formed by the intersection of sectors and zones.

19 **2 Seasonal trends**

20 Seasonal trends are shown in Figure 2 (chl-a), Figure 3 (Vertically Generalised Production Model),
21 Figure 4 (Carbon Based Production Model), and Figure 5 (irradiance at the base of the mixed layer).

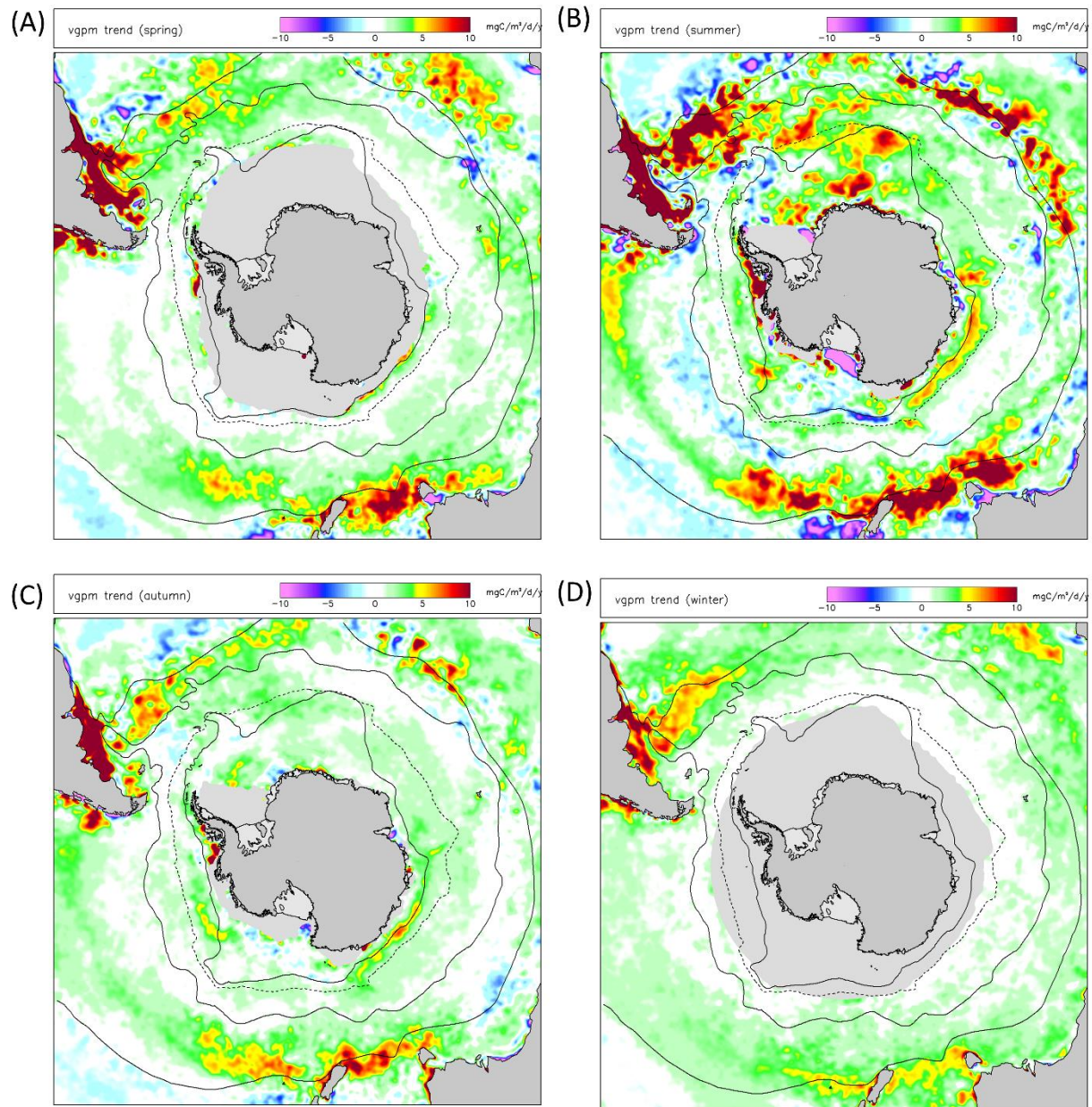
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23 **Figure 2. Seasonal trends in chl-a (indicative of phytoplankton biomass in the mixed layer)**
 24 **between 1997–2019. The value shown is the Sen-slope linear trend ($\text{mg Chl-a m}^{-3}/\text{y}$). Spring:**
 25 **Sep, Oct, Nov; summer: Dec, Jan, Feb; autumn Mar, Apr, May; winter: Jun, Jul, Aug.**

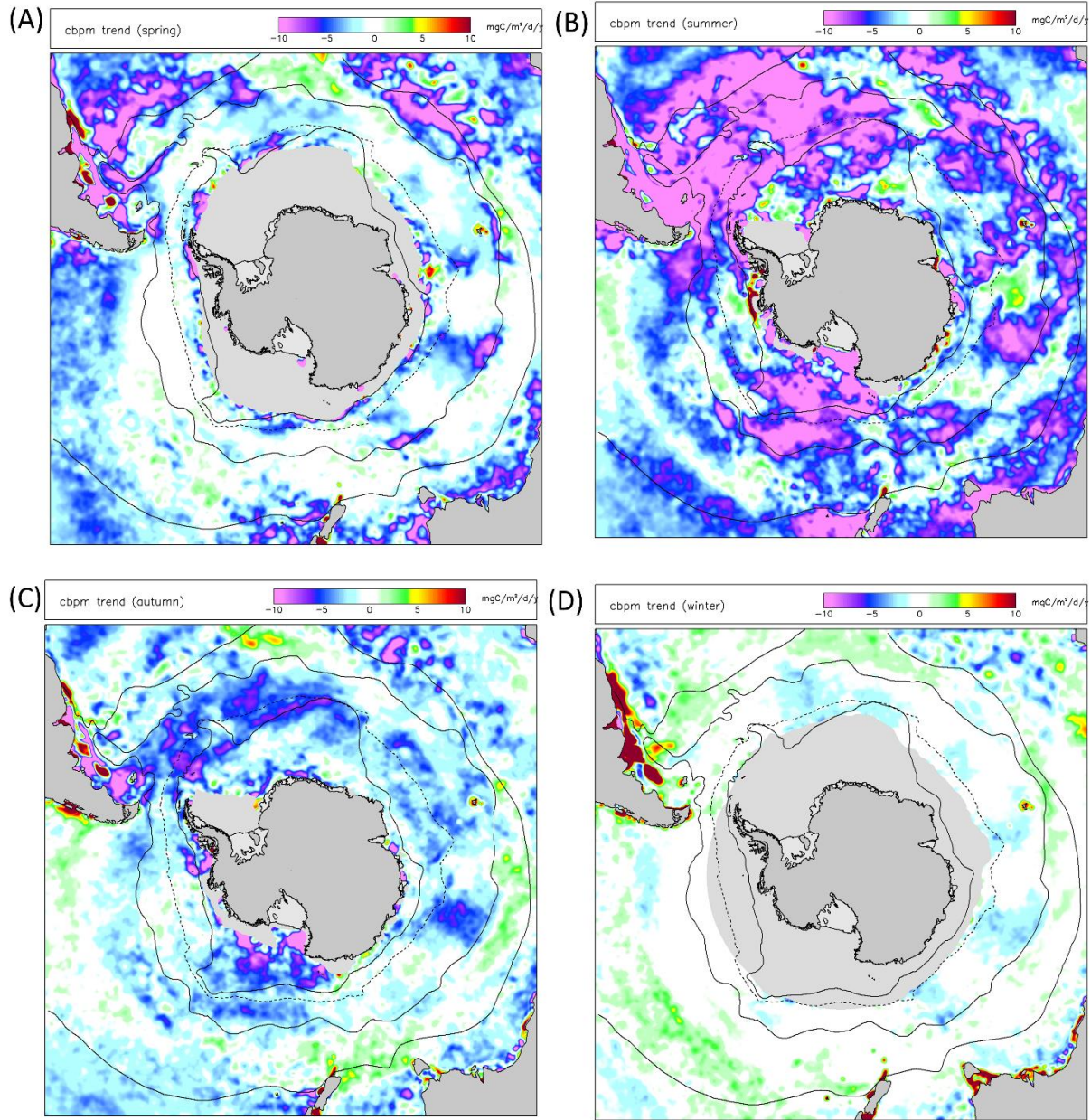
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28 **Figure 3. Seasonal trends in net primary production (NPP) in the mixed layer by the Vertically**
 29 **Generalised Production Model (VGPM) between 1997–2019. The value shown is the Sen-slope**
 30 **linear trend ($\text{mgC/m}^2/\text{d/y}$) by season (Spring: Sep, Oct, Nov; summer: Dec, Jan, Feb; autumn**
 31 **Mar, Apr, May; winter: Jun, Jul, Aug).**

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33 **Figure 4. Seasonal trends in net primary production (NPP) in the mixed layer by the Carbon**
 34 **Based Production Model (CBPM) between 1997–2019. The value shown is the Sen-slope linear**
 35 **trend (mgC/m²/d/y) by season (Spring: Sep, Oct, Nov; summer: Dec, Jan, Feb; autumn Mar,**
 36 **Apr, May; winter: Jun, Jul, Aug).**

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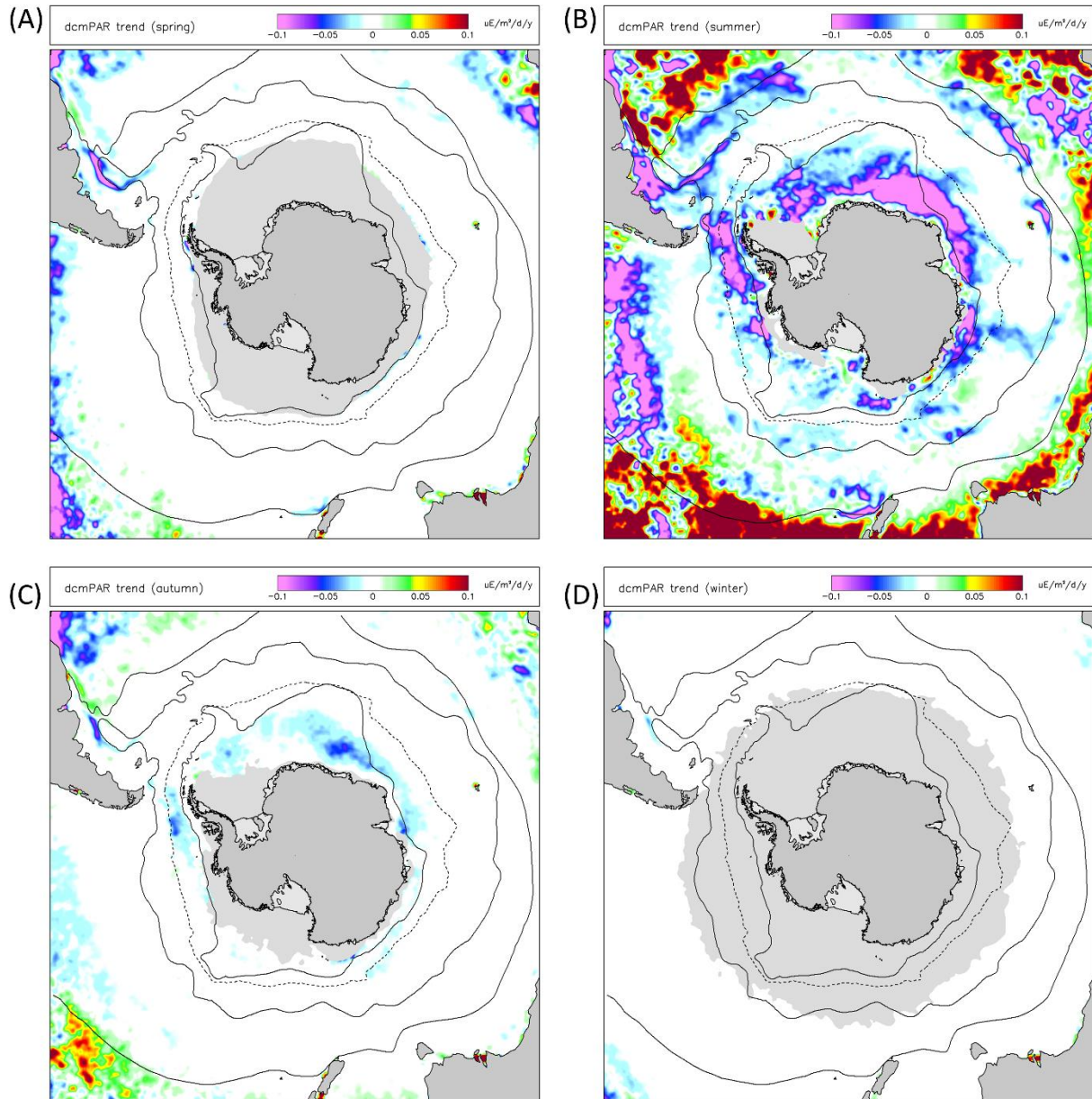


Figure 5. Seasonal trends in E_{DCM} (indicative of phytoplankton primary production in the deep chlorophyll maximum, DCM) between 1997–2019. The value shown is the Sen-slope linear trend ($nE/m^2/d/y$) by season (Spring: Sep, Oct, Nov; summer: Dec, Jan, Feb; autumn Mar, Apr, May; winter: Jun, Jul, Aug).

3 Zonal time-series analysis

Time-series of chl-a summarised by MEASO zone are shown below for chl-a (Figure 6), primary productivity in the mixed layer by VGPM (Figure 7), primary productivity in the mixed layer by CBPM (Figure 8) and irradiance at the base of the mixed layer and concentration of sea ice (Figure 9).

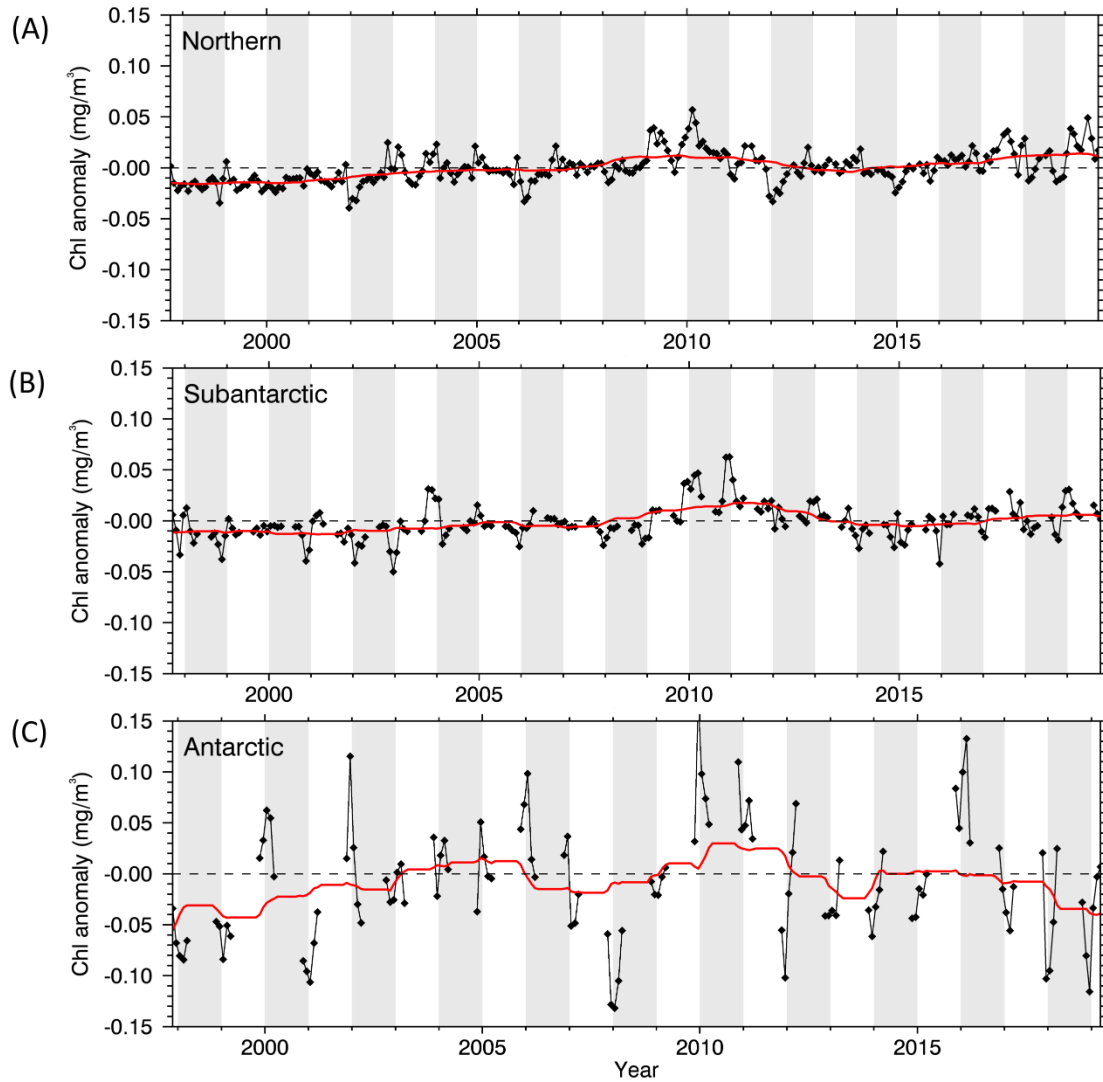
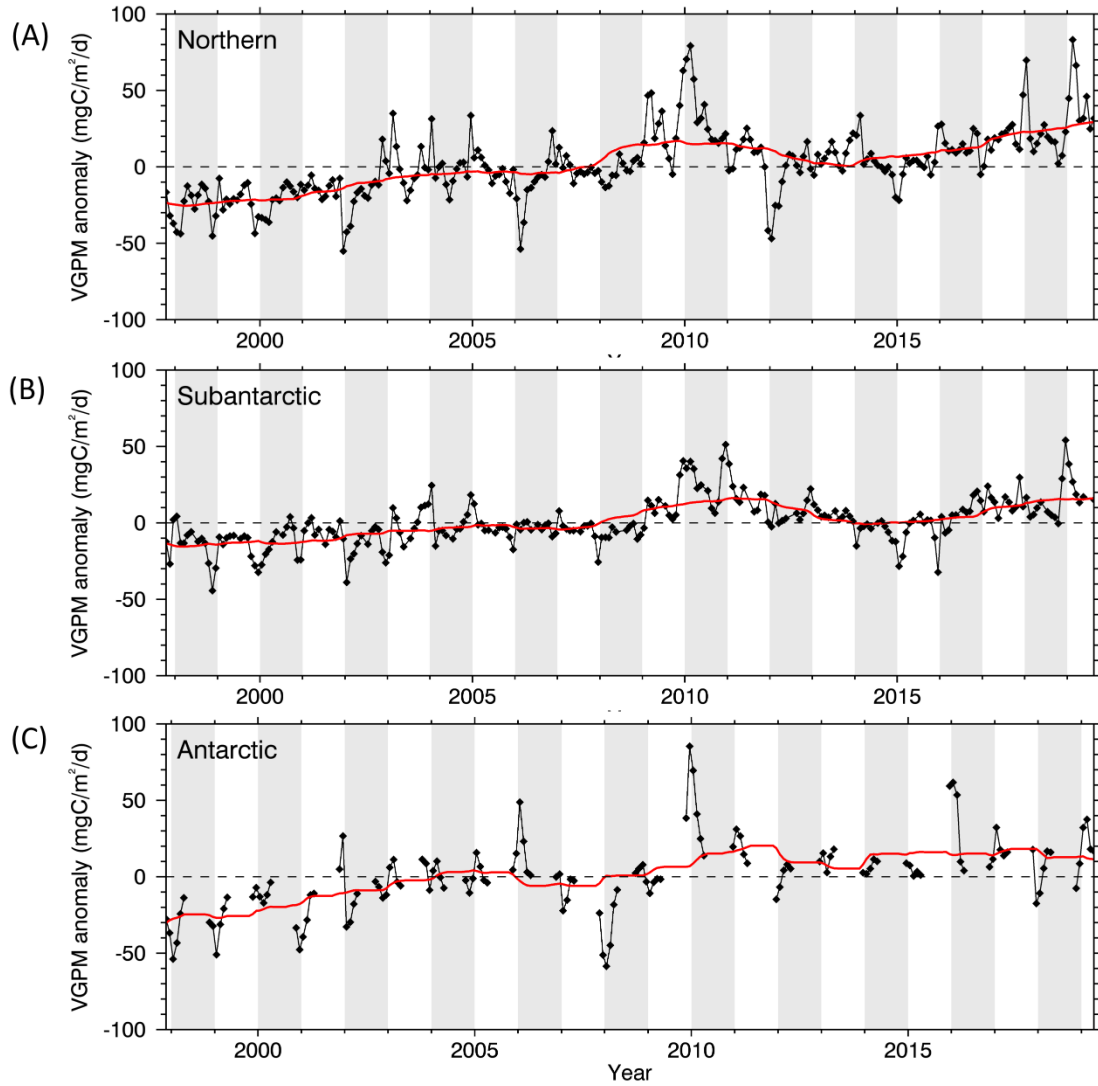


Figure 6. Zonal trends in chl-a concentration: Northern (A); Subantarctic (B); Antarctic (C). Black data are monthly anomalies and the red line is smoothed with a 4-year running mean.



51 **Figure 7. Zonal trends in VGPM: Northern (A); Subantarctic (B); Antarctic (C). Black data**
 52 **are monthly anomalies and the red line is smoothed with a 4-year running mean.**

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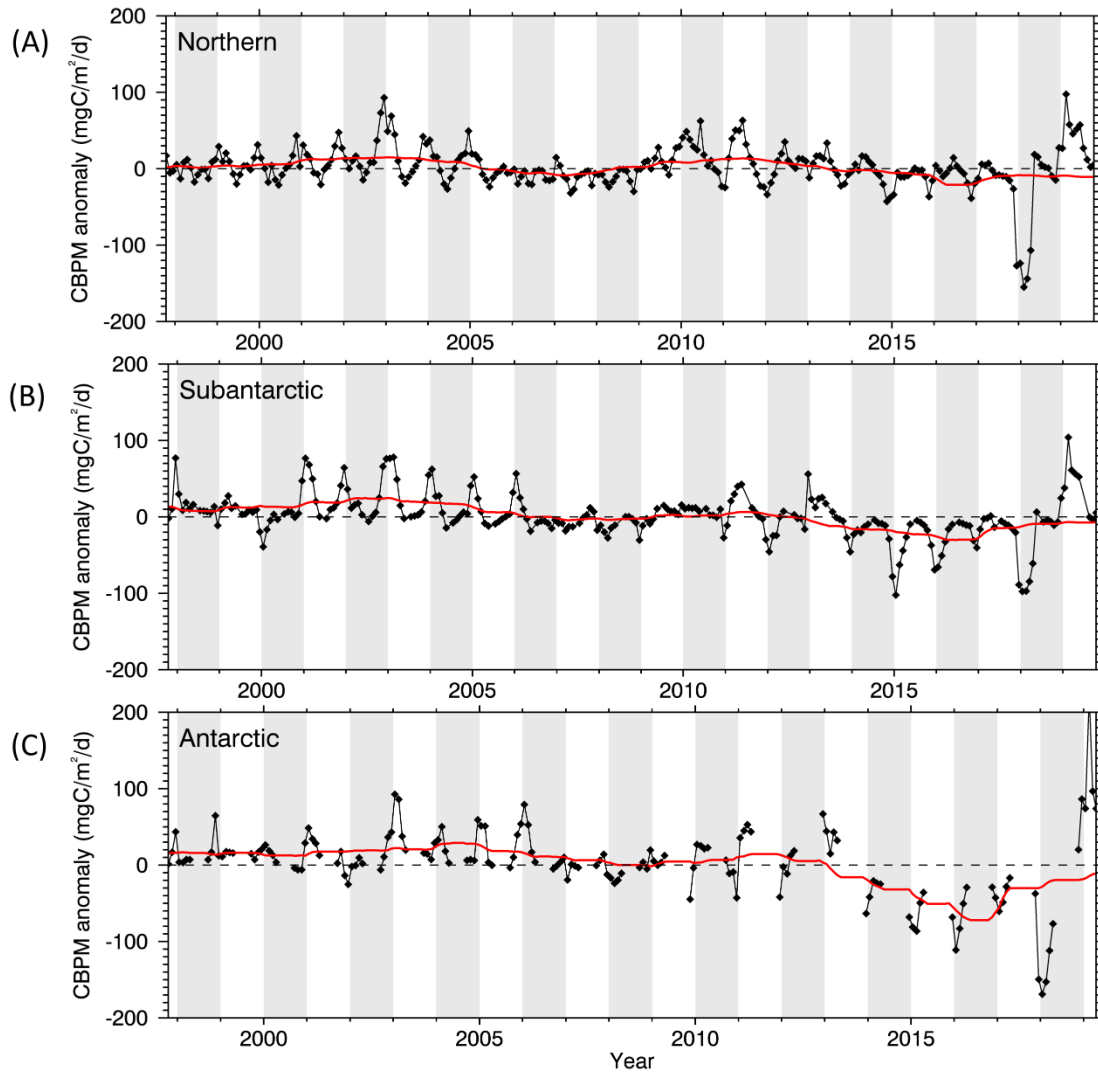


Figure 8. Zonal trends in CBPM: Northern (A); Subantarctic (B); Antarctic (C). Black data are monthly anomalies and the red line is smoothed with a 4-year running mean.

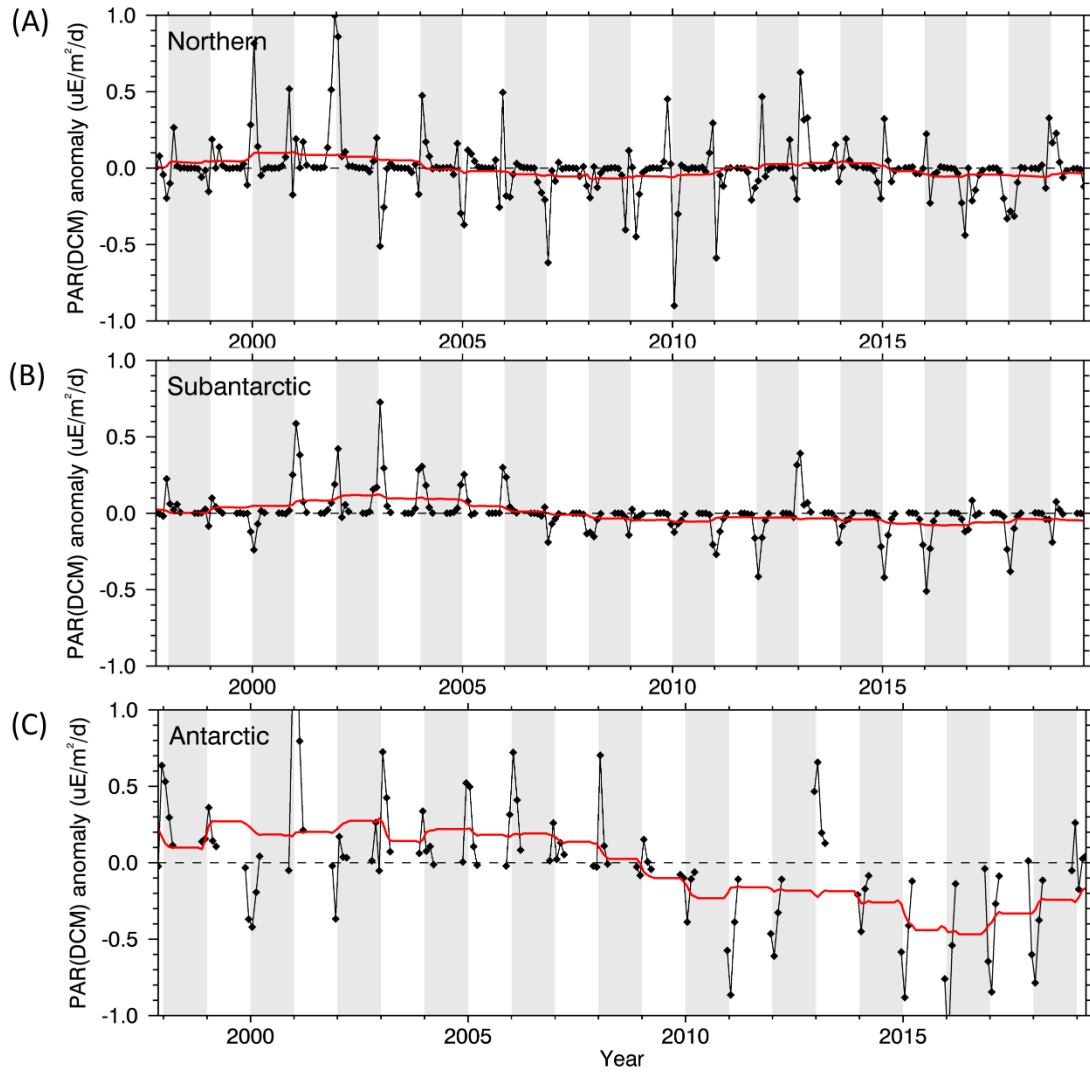
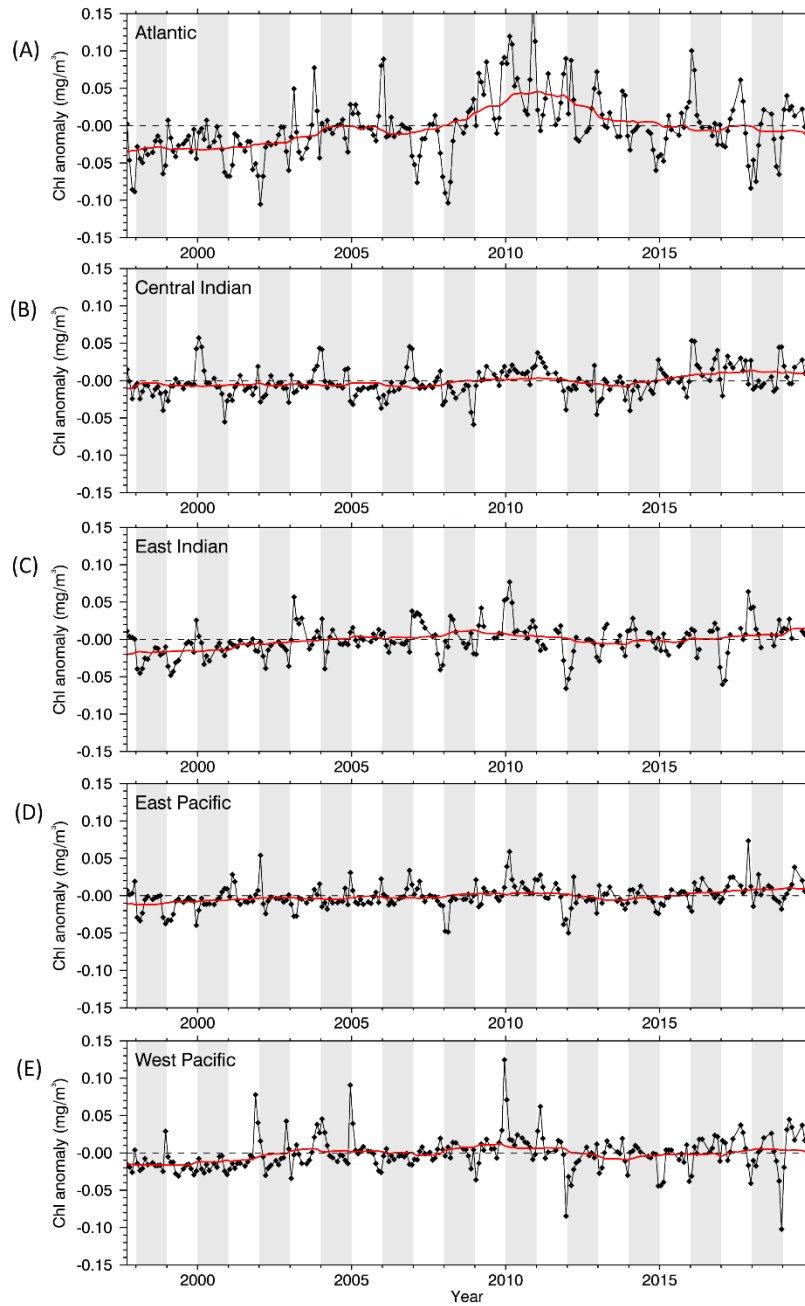


Figure 9. Zonal trends in E_{DCM} (1997–2019). E_{DCM} is indicative of phytoplankton primary production in the deep chlorophyll maximum (DCM): Northern (A); Subantarctic (B); Antarctic (C). Black data are monthly anomalies and the red line is smoothed with a 4-year running mean.

67 **4 Sector time-series analysis**

68 Time-series of chl-a summarised by MEASO sector are shown below for chl-a (Figure 10), primary
69 productivity in the mixed layer by VGPM (Figure 11), primary productivity in the mixed layer by
70 CBPM (Figure 12) and irradiance at the base of the mixed layer and concentration of sea ice (Figure
71 13).

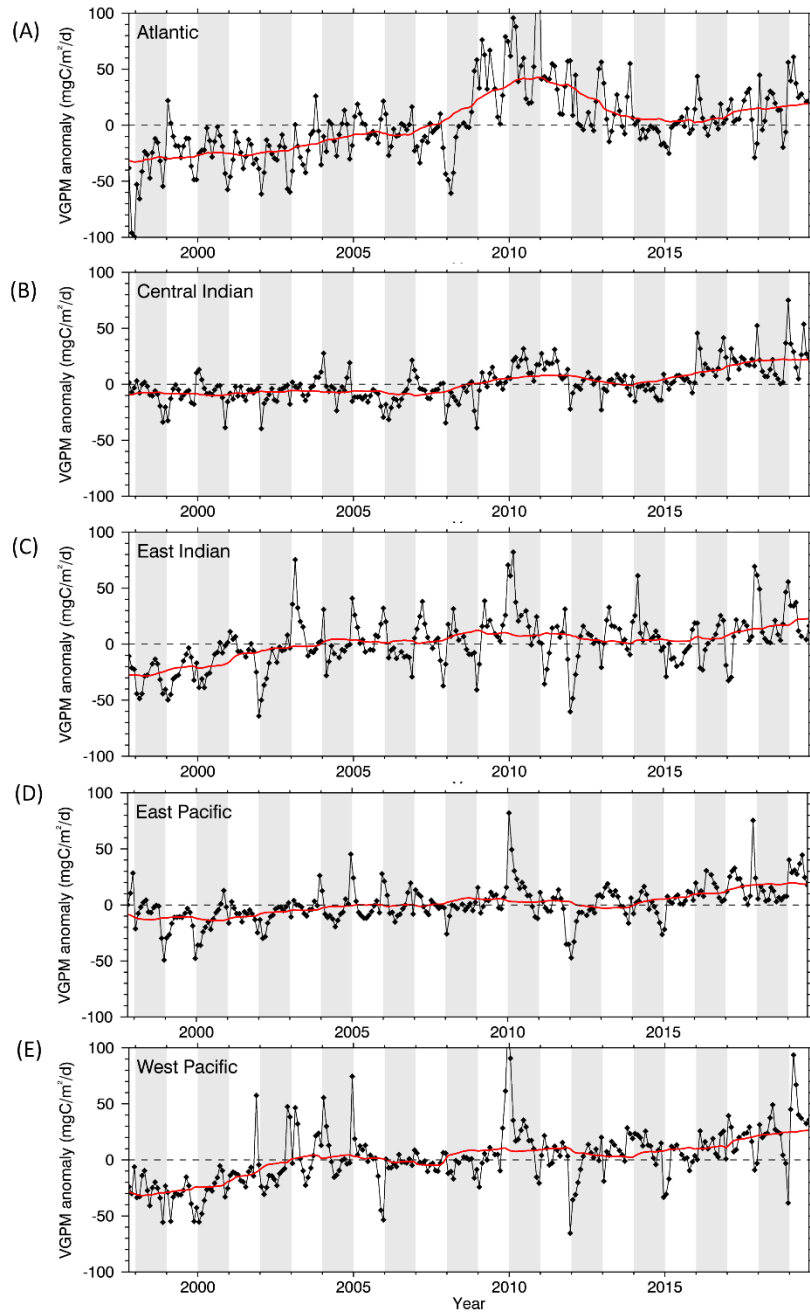
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73 **Figure 10. Sector trends in chl-a concentration: Atlantic (A); Central Indian**
 74 **(C); West Pacific (D); Central Pacific (E). Black data are monthly anomalies and the red line is**
 75 **smoothed with a 4-year running mean.**

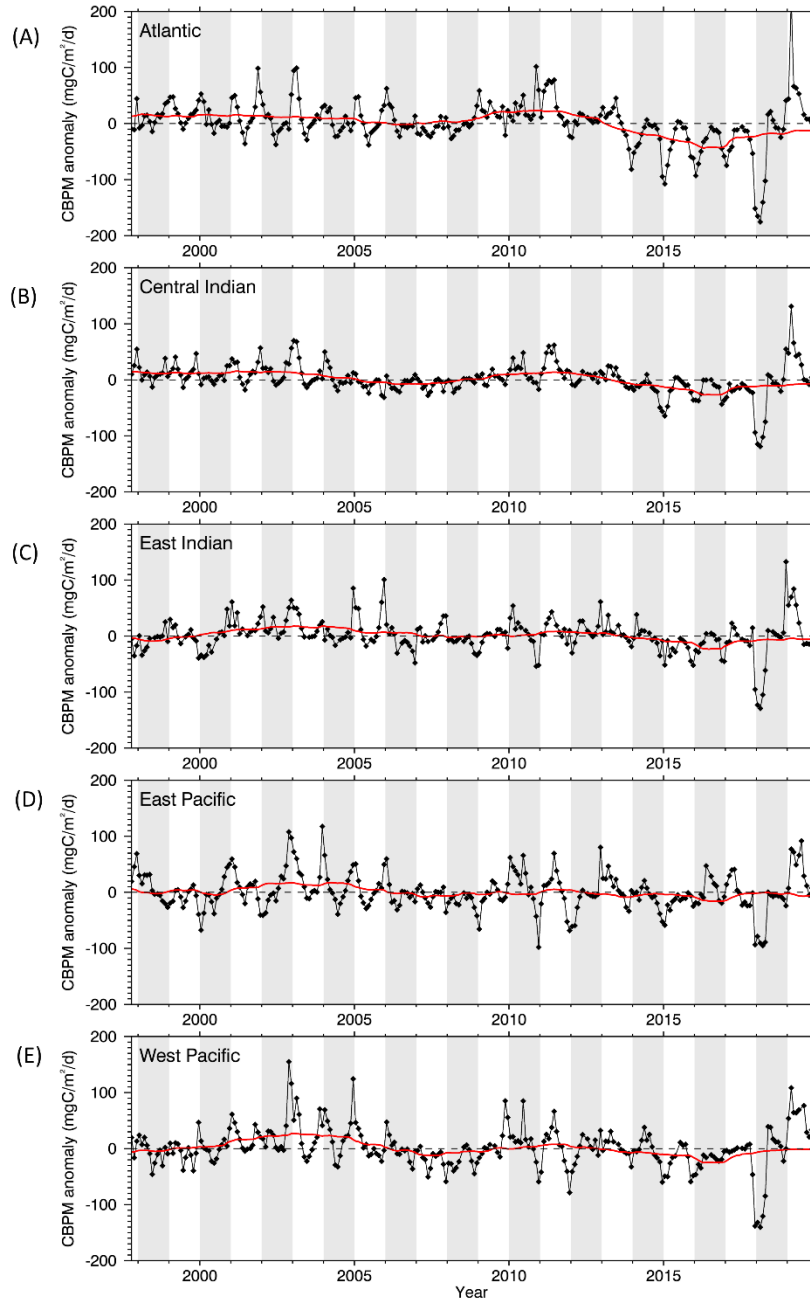
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78 **Figure 11. Sector trends in VGPM: Atlantic (A); Central Indian (B); East Indian (C); West**
 79 **Pacific (D); Central Pacific (E). Black data are monthly anomalies and the red line is smoothed**
 80 **with a 4-year running mean.**

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82 **Figure 12. Sector trends in CBPM: Atlantic (A); Central Indian (B); East Indian (C); West**
 83 **Pacific (D); Central Pacific (E). Black data are monthly anomalies and the red line is smoothed**
 84 **with a 4-year running mean.**

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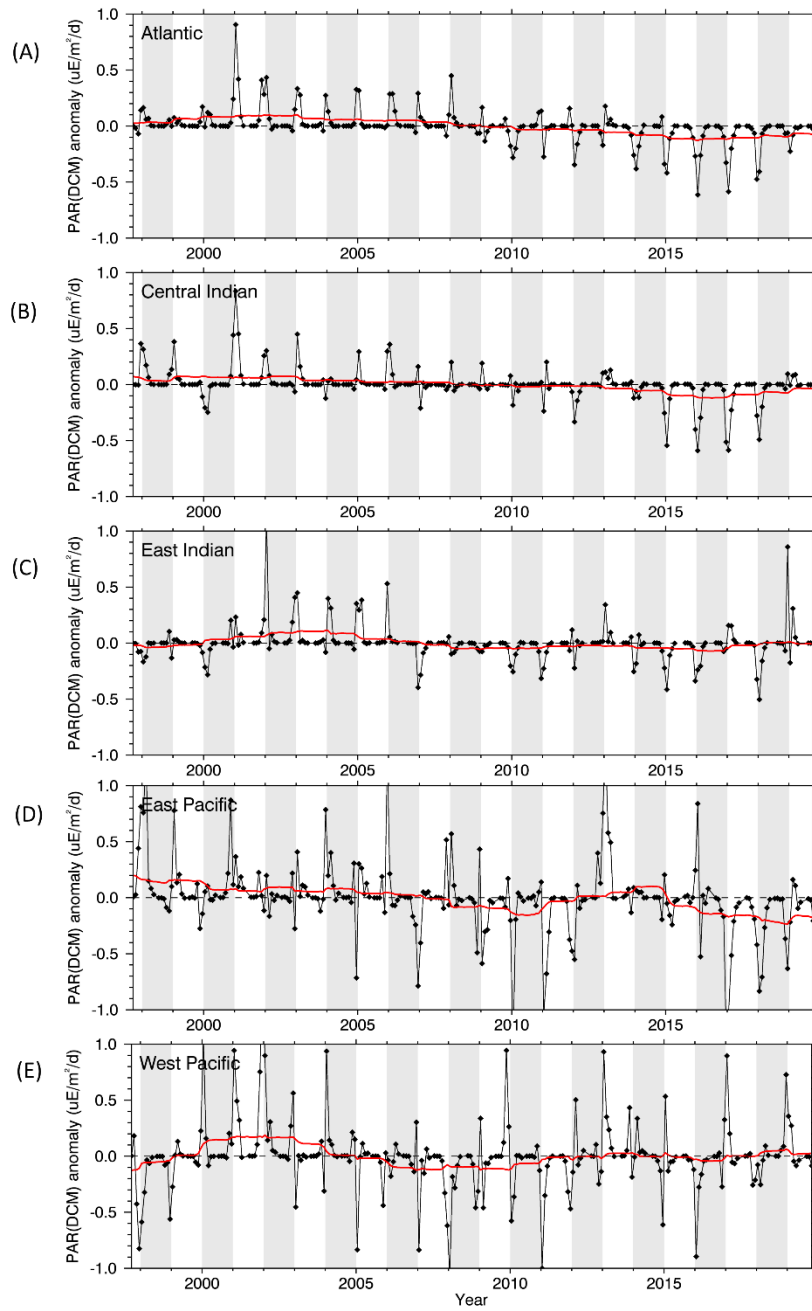


Figure 13. Sector trends in irradiance at the base of the mixed layer (E_{DCM}). Atlantic (A); Central Indian (B); East Indian (C); West Pacific (D); Central Pacific (E). Black data are monthly anomalies and the red line is smoothed with a 4-year running mean.

5 Area time-series analysis

Time-series of chl-a summarised by MEASO area are shown below for chl-a (Figure 14), primary productivity in the mixed layer by VGPM (Figure 15), primary productivity in the mixed layer by CBPM (Figure 16) and irradiance at the base of the mixed layer and concentration of sea ice (Figure 17).

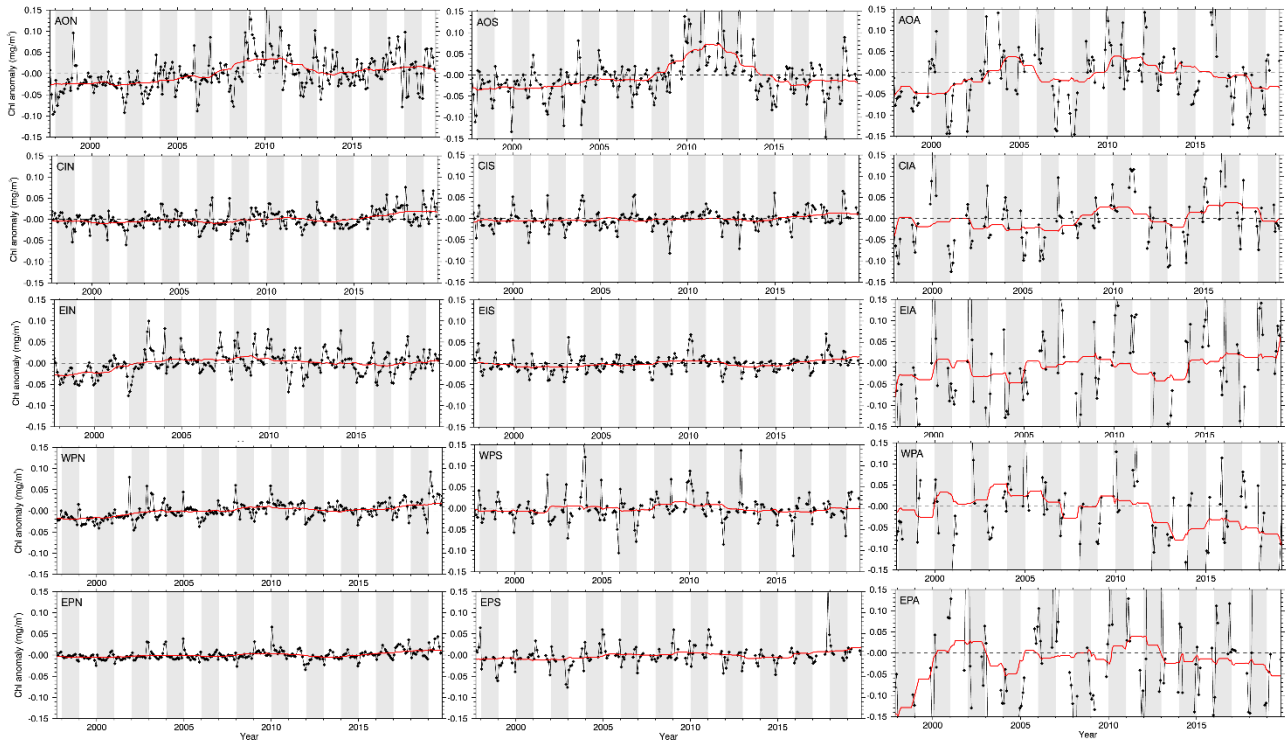


Figure 14. Area trends in chl-a concentration. Black data are monthly anomalies and the red line is smoothed with a 4-year running mean.

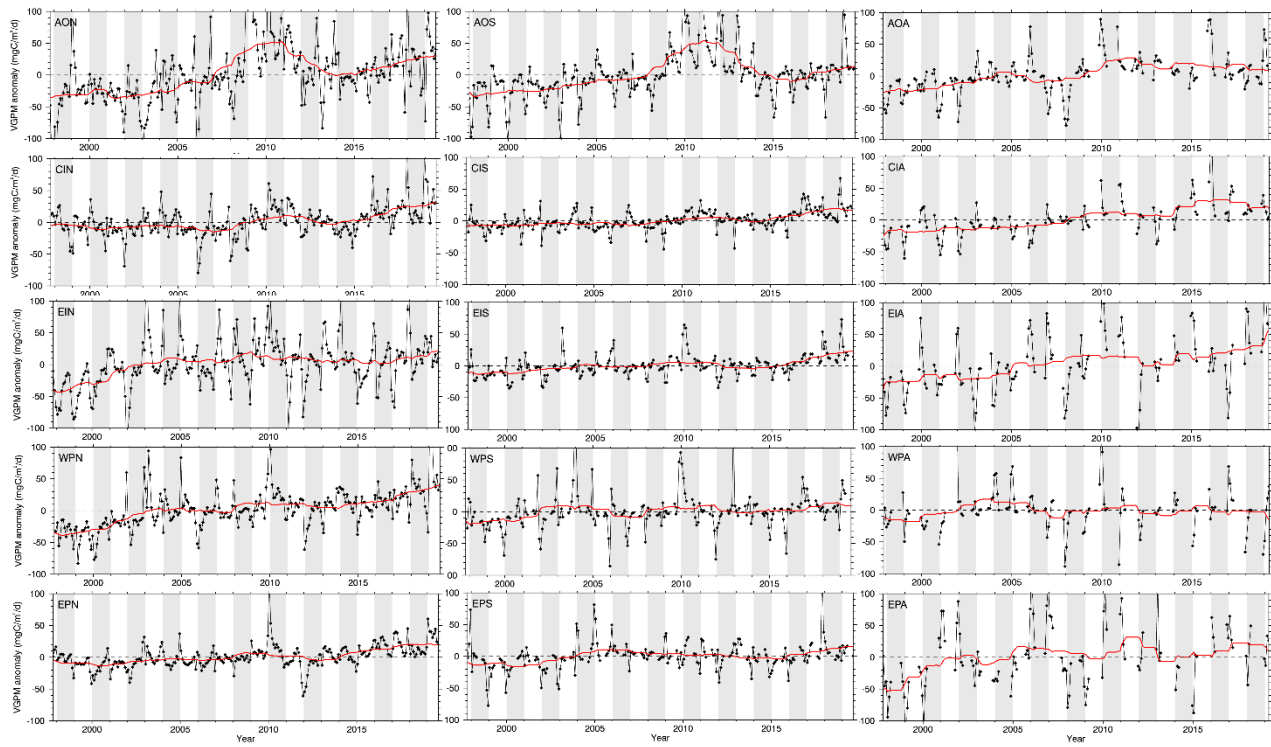
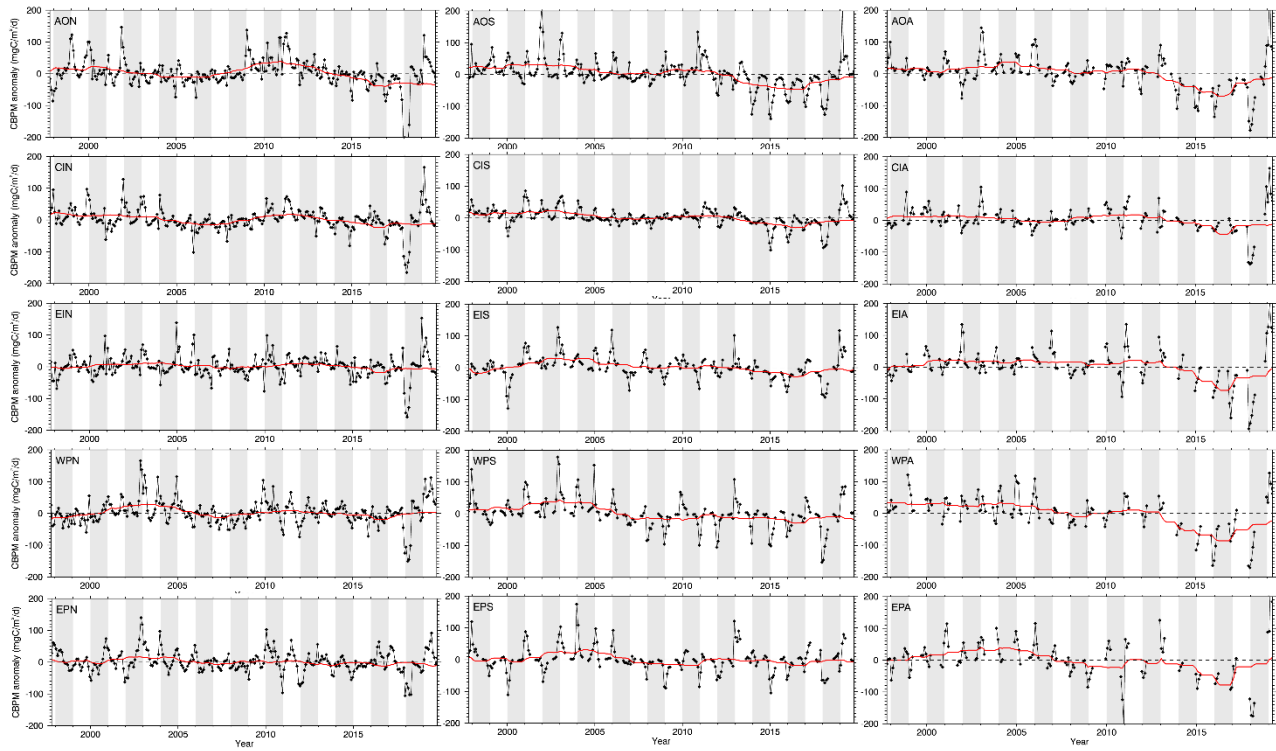


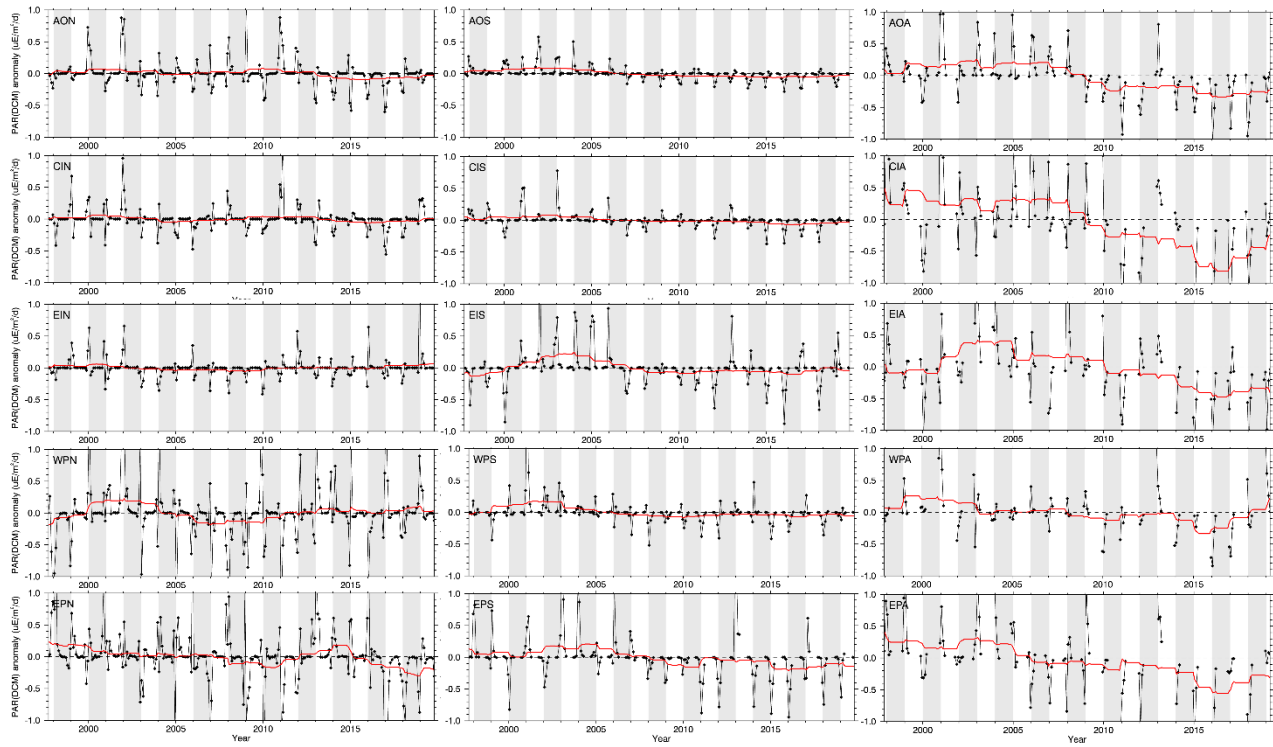
Figure 15. Area trends in VGPM. Black data are monthly anomalies and the red line is smoothed with a 4-year running mean.



105 **Figure 16. Area trends in CBPM. Black data are monthly anomalies and the red line is**
 106 **smoothed with a 4-year running mean.**

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112 **Figure 17. Area trends in irradiance at the base of the mixed layer (E_{DCM}). Black data are**
 113 **monthly anomalies and the red line is smoothed with a 4-year running mean.**

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116 **6 Statistical analysis of trends**

117 Statistical analysis of trends by MEASO zone, sector and area are shown in Table 1 (chl-a), Table 2
118 (VGPM), Table 3 (CBPM) and Table 4 (irradiance at the base of the mixed layer, E_{DCM}).

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Table 1. Analysis of changes in chlorophyll-a concentration (chl-a) by MEASO region 1997–2019. The median value is calculated over the whole time series. N is the number of observations, N* the number of effective degrees of freedom after correction for autocorrelation, Z is the Mann-Kendall trend statistic, p the Mann-Kendall linear trend significance, Sen slope is a measure of the magnitude of the average linear trend with significance: * $p \leq 0.05$ ** $p \leq 0.01$ * $p \leq 0.001$. The final column gives the Sen slope trend as a proportion of the median value.**

	Median	N	N*	Z	p	senSlope	slope/median
	mg/m ³					µg/m ³ /y	%/y
Southern Ocean							
All	0.20	232	39	3.05	0.002	1.1**	0.51
Zones							
Northern	0.20	258	54	4.11	0.000	1.2***	0.63
Subantarctic	0.19	200	44	2.39	0.017	0.79*	0.43
Antarctic	0.36	112	24	0.54	0.592	0.97	0.27
Sectors							
Atlantic	0.28	231	42	2.43	0.015	2.0*	0.69
Central Indian	0.20	233	67	2.63	0.009	0.8**	0.40
East Indian	0.18	212	50	2.33	0.020	1.0*	0.53
East Pacific	0.14	234	88	2.88	0.004	0.60**	0.44
West Pacific	0.19	234	71	3.07	0.002	1.1**	0.59
Areas							
AON	0.29	266	77	3.69	0.000	2.3***	0.78
AOS	0.27	211	46	1.66	0.096	1.5	0.57
AOA	0.34	144	31	0.79	0.430	1.5	0.44
CIN	0.21	264	104	2.40	0.016	0.69*	0.33
CIS	0.18	204	83	2.46	0.014	0.66*	0.36
CIA	0.25	111	23	1.10	0.272	2.2	0.90
EIN	0.19	244	53	1.75	0.080	1.0	0.52
EIS	0.16	194	62	1.74	0.081	0.55	0.36
EIA	0.32	111	30	1.23	0.217	4.3	1.35
WPN	0.17	257	98	5.09	0.000	1.5***	0.85
WPS	0.17	180	75	0.77	0.440	0.28	0.17
WPA	0.40	102	51	-1.36	0.174	-2.6	-0.63
EPN	0.12	256	93	3.33	0.001	0.49***	0.41
EPS	0.14	169	85	1.83	0.068	0.50	0.35
EPA	0.47	118	43	0.68	0.499	2.2	0.48

Table 2. Analysis of changes in net primary production (NPP) by the Vertically-Generalised production Model (VGPM) summarized by MEASO region 1997–2019. See caption Table 1 for other details.

	Median	N	N*	Z	p	senSlope	slope/median
	mgC/m ² /d					mgC/m ² /d/y	%/y
Southern Ocean							
All	221.9	257	35	4.81	0.000	1.8***	0.81
Zones							
Northern	293.6	263	45	5.15	0.000	2.1***	0.71
Subantarctic	168.1	237	42	4.09	0.000	1.2***	0.70
Antarctic	200.2	132	25	3.39	0.001	1.9***	0.95
Sectors							
Atlantic	258.1	257	43	4.02	0.000	2.5***	0.95
Central Indian	212.1	260	72	5.08	0.000	1.2***	0.58
East Indian	222.9	241	46	3.25	0.001	1.6**	0.70
East Pacific	177.6	260	61	4.53	0.000	1.2***	0.67
West Pacific	241.7	255	63	5.41	0.000	2.2***	0.93
Areas							
AON	416.5	263	63	4.13	0.000	3.0***	0.72
AOS	203.8	241	37	2.74	0.006	1.7**	0.82
AOA	164.8	171	29	2.91	0.004	1.8**	1.11
CIN	330.7	263	76	3.37	0.001	1.2***	0.36
CIS	168.9	241	92	5.28	0.000	1.0***	0.59
CIA	156.5	131	36	4.04	0.000	2.1***	1.36
EIN	299.1	263	54	2.76	0.006	1.8**	0.60
EIS	162.5	197	52	3.50	0.000	1.0***	0.64
EIA	180.0	130	26	2.56	0.011	3.1*	1.71
WPN	280.9	263	75	6.01	0.000	2.7***	0.97
WPS	162.4	197	68	2.86	0.004	1.0**	0.59
WPA	209.3	119	44	0.89	0.372	0.4	0.19
EPN	201.8	263	55	4.13	0.000	1.3***	0.63
EPS	136.7	197	82	2.21	0.027	0.6*	0.45
EPA	245.5	112	27	1.70	0.090	2.4	0.96

134 **Table 3. Analysis of changes in net primary production (NPP) by the Carbon Based Production**
 135 **Model (CBPM) summarized by MEASO region 1997–2019. See caption Table 1 for other**
 136 **details.**

	Median	N	N*	Z	p	senSlope	slope/median
	mgC/m ² /d					mgC/m ² /d/y	%/y
Southern Ocean							
All	163.5	259	27	-1.38	0.167	-0.8	-0.51
Zones							
Northern	199.4	265	32	-0.63	0.527	-0.3	-0.17
Subantarctic	107.3	239	30	-2.45	0.014	-1.4*	-1.27
Antarctic	223.0	152	23	-1.79	0.073	-2.3	-1.04
Sectors							
Atlantic	174.8	259	37	-1.68	0.093	-1.3	-0.76
Central Indian	124.7	262	33	-2.00	0.045	-1.0*	-0.82
East Indian	127.5	243	51	-1.02	0.306	-0.5	-0.38
East Pacific	188.2	262	39	-0.70	0.482	-0.5	-0.25
West Pacific	190.9	257	39	-0.70	0.482	-0.5	-0.26
Areas							
AON	242.2	265	45	-0.75	0.452	-0.5	-0.22
AOS	131.4	243	46	-3.17	0.002	-2.3**	-1.73
AOA	193.4	177	29	-1.86	0.063	-2.3	-1.17
CIN	153.6	265	57	-1.31	0.190	-0.7	-0.43
CIS	103.6	243	30	-2.56	0.010	-1.5*	-1.44
CIA	263.5	146	35	-0.98	0.329	-0.9	-0.33
EIN	112.4	265	107	-0.03	0.979	0.0	-0.01
EIS	132.1	199	34	-1.44	0.151	-1.1	-0.86
EIA	284.6	140	23	-0.78	0.437	-1.2	-0.44
WPN	223.7	265	49	0.21	0.831	0.1	0.06
WPS	102.8	199	40	-2.25	0.024	-1.5*	-1.48
WPA	205.3	126	28	-2.53	0.011	-4.2*	-2.07
EPN	229.0	265	41	-0.62	0.532	-0.4	-0.19
EPS	81.3	199	40	-1.01	0.313	-0.6	-0.78
EPA	256.4	119	30	-1.56	0.120	-2.8	-1.11

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139 **Table 4. Analysis of changes in irradiance at the base of the mixed layer by MEASO region**
 140 **1997–2019. See caption Table 1 for other details.**

	Median	N	N*	Z	p	senSlope	slope/median
	$\mu\text{E}/\text{m}^2/\text{d}$					$\text{nE}/\text{m}^3/\text{d}/\text{y}$	$\%/ \text{y}$
Southern Ocean							
All	0.10	231	76	-3.84	0.000	-3.1***	-3.15
Zones							
Northern	0.12	257	147	-2.41	0.016	-0.7*	-0.63
Subantarctic	0.04	200	55	-3.12	0.002	-2.0**	-5.41
Antarctic	0.51	105	32	-3.23	0.001	-25.8**	-5.07
Sectors							
Atlantic	0.04	230	71	-4.26	0.000	-2.6***	-6.58
Central Indian	0.02	232	66	-2.59	0.009	-0.7**	-3.24
East Indian	0.04	210	117	-1.69	0.090	-0.3	-0.72
East Pacific	0.31	233	106	-3.80	0.000	-6.0***	-1.92
West Pacific	0.20	233	112	-0.88	0.379	-0.5	-0.24
Areas							
AON	0.04	265	111	-1.75	0.081	-0.2	-0.42
AOS	0.03	209	74	-4.37	0.000	-2.6***	-8.67
AOA	0.23	128	42	-3.57	0.000	-16.4***	-7.05
CIN	0.02	263	142	-2.12	0.034	-0.2*	-0.71
CIS	0.03	201	77	-2.87	0.004	-1.0**	-3.62
CIA	0.74	103	37	-2.91	0.004	-38.5**	-5.23
EIN	0.01	243	243	0.69	0.492	0.0	0.25
EIS	0.04	194	78	-1.77	0.077	-0.7	-1.95
EIA	0.49	103	33	-1.83	0.068	-17.7	-3.65
WPN	0.16	256	136	-0.12	0.904	0.0	-0.03
WPS	0.03	180	90	-2.68	0.007	-1.5**	-6.04
WPA	0.33	91	35	-1.65	0.098	-8.9	-2.70
EPN	0.27	255	147	-3.30	0.001	-3.6***	-1.34
EPS	0.06	169	55	-3.00	0.003	-4.2**	-7.03
EPA	0.68	103	47	-3.23	0.001	-25.8**	-3.77