



Supplement of

Development of the MIROC-ES2L Earth system model and the evaluation of biogeochemical processes and feedbacks

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Table S1 Same as Table 3 but for the other nine experiments (CTL-D, HIST-NOLUC, HIST-BGC, 1PPY, 1PPY-BGC, 1PPY-RAD, NO-NR, NO-NRD, and NO-FD).

	CTL-D (Last 10 years)	HIST- NOLUC (2000s)	HIST- BGC (2000s)	1PPY (Last 10 years)	1PPY- BGC (Last 10 years)	1PPY- RAD (Last 10 years)	NO-NR (Last 10 years)	NO- NRD (Last 10 years)	NO-FD (Last 10 years)
Gross primary productivity (PgC yr ⁻¹)	108.2	128.3	123.4	185.7	178.7	105	108.2	108.2	108.2
Net primary productivity (PgC yr ⁻ ¹)	57.4	68.6	67.4	98.6	97.9	53.6	57.4	57.4	57.4
Heterotrophic respiration (PgC yr ⁻¹)	56.6	64.4	58.9	92.6	89.4	55.7	56.6	56.6	56.6
Net carbon uptake ^{*1} (PgC yr ⁻¹)	0	3.2	3	4.7	7.2	-2.9	0	0	0
Vegetation carbon (PgC)	536.9	624.7	544.9	924.9	918.3	502.1	536.9	536.9	536.9
Soil organic carbon (PgC)	1480.8	1567.4	1515.9	1772.7	2013.2	1272.3	1480.8	1480.8	1480.8
Biological fixation ^{*2} (TgN yr ⁻¹)	96.8	98.9	134.5	107.5	103.8	100.5	96.8	96.8	96.8
Deposition (TgN yr ⁻¹)	19.6	65.5	65.5	19.6	19.6	19.6	19.6	19.6	19.6
Fertilizer (TgN yr ⁻¹)	0	0	115.7	0	0	0	0	0	0

N ₂ emission (TgN yr ⁻ ')	71.7	81.2	109.9	67.6	55	88.8	71.7	71.7	71.7
N ₂ O emission (TgN yr ⁻¹)	9.4	9.7	12.9	8.3	5.8	14.4	9.4	9.4	9.4
NH3 emission (TgN yr ⁻¹)	2	2.2	19.5	2.1	1.1	3.9	2	2	2
N leaching (TgN yr ⁻¹)	17.3	21	28.1	21.1	8.6	49.1	17.3	17.3	17.3
Net ecosystem nitrogen uptake ^{*3} (TgN yr ⁻¹)	0.3	26.1	47.8	3	35.7	-58.6	0.3	0.3	0.3
Vegetation nitrogen (PgN)	4	4.3	3.8	4.6	3.6	4.3	4	4	4
Soil total nitrogen (PgN)	74.9	75.9	75.7	75.2	78.5	70.8	74.9	74.9	74.9

Table S2 Same as Table 4 but for the other nine experiments (CTL-D, HIST-NOLUC, HIST-BGC, 1PPY, 1PPY-BGC, 1PPY-RAD, NO-NR, NO-NRD, and NO-FD).

	CTL-D (Last 10 years)	HIST- NOLUC (2000s)	HIST- BGC (2000s)	1PPY (Last 10 years)	1PPY- BGC (Last 10 years)	1PPY- RAD (Last 10 years)	NO-NR (Last 10 years)	NO- NRD (Last 10 years)	NO-FD (Last 10 years)
Net primary productivity (PgC yr ⁻ ¹)	28.7	28.2	29.1	26.1	27.9	27.2	28.0	27.7	26.9
Sinking particulate organic carbon at 100m (PgC yr ⁻¹)	8.0	7.8	8.1	7.1	7.7	7.4	7.7	7.7	7.1
Nitrogen fixation (TgN yr ⁻¹)	130.2	126.5	123.2	117.0	124.6	127.8	122.6	132.6	78.8
Nitrogen deposition (TgN y (TgN yr ⁻¹)	14.2	35.2	35.2	14.2	14.2	14.2	14.2	0	14.2
Riverine nitrogen input (TgN yr ⁻¹)	17.6	21.5	28.5	23.6	8.6	54.3	0	0	17.6
Denitrification (TgN yr ⁻¹)	147.8	156.4	171.2	117.0	138.4	143.5	133.6	133	92.6
N ₂ O emission (TgN yr ⁻¹)	4.5	4.3	4.4	4.0	4.4	4.2	4.4	4.4	4.2
Nitrogen flux into the sediment (TgN yr ⁻¹)	0.012	0.013	0.013	0.011	0.012	0.012	0.011	0.011	0.012
N cycle imbalance (TgN yr ⁻¹)	9.7	22.5	11.3	33.8	4.6	48.6	-1.2	-4.8	13.8
Atmosphere-ocean CO ₂ flux (PgC yr ⁻¹)	-0.2	-2.4	-2.5	-4.9	-6.3	0.03	-0.12	-0.05	-0.03

Carbon flux into the sediment (Pg (PgC yr ⁻ ¹)	0.068	0.072	0.071	0.063	0.069	0.07	0.064	0.064	0.07
Mean O ₂ concentration (mmol m ⁻³)	191.2	189.8	191.2	181.3	191.2	181.1	191.5	191.6	194.1
Hypoxic volume $(10^{15} \text{ m}^3; [O_2] < 80$ mmol m ⁻³)	33.8	34.5	34.2	41	32.9	43.3	32.2	32.1	25.1
Suboxic volume (10 ¹⁵ m ³ ; [O ₂] < 5 mmol m ⁻ ³)	2.3	2.7	3.0	2.1	2.1	2.3	2.1	2.1	1.2

Table S3 Drift in % ky⁻¹ for oxygen(O2), nitrate(NO3) and total alkalinity minus DIC (Alk-DIC) at surface, 150 and
2000m. The drift has been computed over the last 250 years of the spin-up simulation.

	O ₂	NO ₃	Alk-DIC
Surface	-0.04	3.0	0.21
150m	-0.76	1.85	0.07
2000m	0.44	0.29	0.56



Structure of nitrogen pool and flow in the land ecosystem component model. Boxes colored green, red, and blue represent vegetation N, soil organic N, and inorganic N, respectively. Arrows indicate internal N flow within land ecosystem (black), N flow into ecosystem (orange), and N flow out of ecosystem (cyan). Bold characters represent the names of N cycle processes/pools and the italic text indicates variable names.

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Distributions of (a) vegetation types used for VISIT-e (b) crop fraction (%) in 1850, and (c) crop fraction (%) in 2014. Vegetation types are based on MODIS vegetation cover category: 1 = evergreen needleleaf forest, 2 = evergreen broadleaf forest, 3 = deciduous needleleaf forest, 4 = deciduous broadleaf forest, 5 = mixed forest, 6 = closed shrubland, 7 = open shrubland, 8 = woody savanna, 9 = savanna, 10 = grassland, 11 = permanent wetland, and 12 = desert. Cropland is not included in the vegetation map, but it is simulated as one of the model tiles, the areal fraction of which follows CMIP6 forcing (LUH2 (Ma et al., 2019); http://luh.umd.edu).



Schematic of biogeochemical compartments and flows in OECO-v2.



Historical emissions of labile Fe from biomass burning (red lines) and fossil fuel and biofuel combustion (black lines) during 1750–2014.



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History of MIROC-ES2L development and the spin-up presented by changes in (a) global mean 2 m air temperature, (b) atmosphere–land CO₂, and (c) atmosphere–ocean CO₂ flux (for CO₂ flux, positive means uptake). Colors represent experimental sets in development phases. Spin-up started at January 2017 (Exp. 01, black line) with a fully integrated system (i.e., physical core plus biogeochemical components). Spin-up ended at January 2019 after a series of final phase spin-up (Exp. 15, 16, 17, and 18 colored gray, brown, green, and blue, respectively). All simulations performed in this study were initiated from the endpoint in the plots. Vertical dashed lines represent the time at which part of the initial conditions of MIROC-ES2L was replaced by that created by the offline component models. For example, at year 7283, the initial condition of ocean biogeochemistry was replaced by that created by the offline OECOv2 spin-up after 3000 years with majorly updated source code. After the beginning of Exp. 15 (gray line, started at year 7283), continuous spin-up was performed by MIROC-ES2L for 2483 years with minor source code modifications.

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Figure S6

Same as Fig. 4 but absolute precipitation rate of GPCP is shown in the right.



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Annual cycle of relationship between snow fraction (y-axis) and LAI (x-axis) in the northern high-latitude land region based on 2000–2014 climatology. Colored dots indicate monthly mean snow fraction and LAI averaged for 50° – 80° N. Left panel is derived from MODIS data and the right panel is derived from a historical run of MIROC-ES2L.

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Same as Fig. 9 but for HIST-NOLUC simulation.



Zonally averaged GPP seasonality [gC m⁻² day⁻¹] of MIROC-ES2L (left) and Jung et al. (2011) (right), presented as the monthly climatology in the 2000s.



Zonally averaged distribution of AOU during the 2000s in the observations from WOA2013 (a) and in the model (b). 95 Left and right panels show Atlantic and Pacific oceans, respectively.



Figure S11

