Supplement of "Further improvement and evaluation of nudging in the E3SM Atmosphere Model version 1 (EAMv1)"

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Simulation	CLDTOT	LWP	IWP	TMQ	PRECL	PRECC	PRECT	AODVIS
unit	unitless	${ m g}~{ m m}^{-2}$	${ m g~m^{-2}}$	${\rm kg}~{\rm m}^{-2}$	${\rm mm}~{\rm day}^{-1}$	${\rm mm}~{\rm day}^{-1}$	${\rm mm}~{\rm day}^{-1}$	unitless
CLIM	0.683	55.168	10.659	25.526	1.342	1.760	3.102	0.146
DNDG_UV6	0.679 (-0.004)	54.520 (-0.649)	10.740 (0.081)	25.505 (0.021)	1.328 (-0.013)	1.753 (-0.008)	3.081(-0.021)	0.141 (-0.004)
RNDG_UV6	0.682 (-0.001)	54.924 (-0.244)	10.736 (0.076)	25.572 (0.045)	1.335 (-0.007)	1.758 (-0.003)	3.093 (-0.009)	0.144 (-0.002)
RNDG_UV3	0.682 (0.000)	55.104 (-0.065)	10.687 (0.028)	25.543 (0.017)	1.340 (-0.001)	1.759 (-0.002)	3.099 (-0.003)	0.145 (-0.001)
RNDG_UV1	0.684 (0.000)	55.175 (0.007)	10.675 (0.016)	25.532 (0.006)	1.342 (0.000)	1.759 (-0.001)	3.101(-0.001)	0.146 (-0.000)
DNDG_UVT6	0.666 (-0.017)	53.574 (-1.594)	10.515 (-0.144)	25.175 (-0.352)	1.357 (0.016)	1.739 (-0.022)	3.096 (-0.006)	0.143 (-0.002)
RNDG_UVT6	0.680 (-0.003)	55.881 (0.713)	10.713 (0.053)	25.548 (0.022)	1.311 (-0.031)	1.783 (0.023)	3.094 (-0.008)	0.144 (-0.002)
RNDG_UVT3	0.682 (-0.001)	55.303 (0.134)	10.666 (0.006)	25.530 (0.004)	1.332 (-0.009)	1.768 (0.008)	3.101 (-0.001)	0.145 (-0.001)
RNDG_UVT1	0.682 (-0.001)	55.117 (-0.051)	10.668 (0.008)	25.525 (-0.001)	1.340 (-0.002)	1.762 (0.002)	3.102 (-0.000)	0.146 (-0.000)
Simulation	FNET	FSNT	FLNT	FLNTC	CRE	SWCF	LWCF	
unit	${\rm W}{\rm m}^{-2}$	${\rm W~m^{-2}}$	${\rm W~m^{-2}}$	${ m W~m^{-2}}$	${\rm W~m^{-2}}$	${\rm W~m^{-2}}$	${\rm W~m^{-2}}$	
CLIM	-0.655	238.565	239.220	263.593	-25.921	-50.294	24.373	
DNDG_UV6	-0.234 (0.421)	238.884 (0.319)	239.117 (-0.103)	263.438 (-0.154)	-25.683 (0.238)	-50.004 (0.290)	24.321 (-0.052)	
RNDG_UV6	-0.515 (0.140)	238.595 (0.030)	239.110 (-0.110)	263.473 (-0.120)	-25.907 (0.014)	-50.270 (0.023)	24.363 (-0.010)	
RNDG_UV3	-0.619 (0.036)	238.537 (-0.027)	239.156 (-0.064)	263.556 (-0.037)	-25.926 (-0.005)	-50.325 (-0.032)	24.399 (0.027)	
RNDG_UV1	-0.642 (0.013)	238.524 (0.041)	239.166 (-0.054)	263.581 (-0.012)	-25.920 (0.001)	-50.335 (-0.042)	24.415 (0.042)	
DNDG_UVT6	0.324 (0.979)	240.622 (2.057)	240.297 (1.078)	263.887 (0.295)	-24.659 (1.262)	-48.249 (2.045)	23.590 (-0.783)	
RNDG_UVT6	-0.478 (0.177)	238.903 (0.338)	239.382 (0.162)	263.392 (-0.201)	-26.007 (0.086)	-50.017 (0.277)	24.010 (-0.362)	
RNDG_UVT3	-0.577(0.078)	238.745 (0.181)	239.322 (0.102)	263.533 (-0.060)	-25.920 (0.001)	-50.131 (0.163)	24.211 (-0.162)	
RNDG_UVT1	-0.587 (0.068)	238.676 (0.111)	239.263 (-0.043)	263.580 (-0.012)	-25.866 (0.055)	-50.183 (0.111)	24.317 (-0.055)	

Table S2. As in Table S1 but for the simulations nudged to ERA reanalyses (ERA-interim and ERA5). The result of CLIM simulation is given as the ensemble mean of global annual mean \pm one standard deviation of the 5 ensemble members. Numbers in the parentheses show the differences of global annual means between nudged simulations and CLIM. See Table 1 and Section 2.3 in the main text for the detailed setups for each simulation.

Simulation	CLDTOT	LWP	IWP	TMQ	PRECL	PRECC	PRECT	AODVIS
unit	unitless	${ m g~m^{-2}}$	${ m g}~{ m m}^{-2}$	${\rm kg}~{\rm m}^{-2}$	${\rm mm}~{\rm day}^{-1}$	${\rm mm}~{\rm day}^{-1}$	${\rm mm}~{\rm day}^{-1}$	unitless
CLIM	0.674 ± 0.005	53.780 ± 0.819	10.659 ± 0.029	25.322 ± 0.132	1.320 ± 0.013	1.765 ± 0.003	3.084 ± 0.011	0.143 ± 0.002
DNDG_ERAI_UV6	0.650 (-0.023)	53.782 (-0.002)	10.111 (-0.548)	25.295 (-0.027)	1.352 (0.032)	1.681 (-0.084)	3.032 (-0.052)	0.129 (-0.015)
RNDG_ERAI_UV6	0.651 (-0.022)	54.220 (0.440)	10.125 (-0.534)	25.329 (-0.007)	1.359 (0.039)	1.691 (-0.073)	3.050 (-0.034)	0.130 (-0.013)
RNDG_ERA5_UV6	0.663 (-0.011)	54.588 (0.808)	10.216 (-0.443)	25.362 (0.039)	1.348 (0.035)	1.700 (-0.065)	3.048 (-0.036)	0.131 (-0.012)
RNDG_ERA5_UV3	0.664 (-0.010)	54.728 (0.948)	10.182 (-0.478)	25.330 (0.007)	1.355 (0.035)	1.700 (-0.065)	3.055 (-0.030)	0.132 (-0.011)
RNDG_ERA5_UV1	0.664 (-0.009)	54.745 (0.965)	10.163 (-0.496)	25.302 (0.020)	1.356 (0.036)	1.699 (-0.066)	3.055 (-0.029)	0.132 (-0.011)
DNDG_ERAI_UVT6	0.635 (-0.038)	59.264 (5.484)	9.962 (-0.697)	25.302 (-0.020)	1.293 (-0.027)	1.633 (-0.132)	2.926 (-0.159)	0.136 (-0.007)
RNDG_ERAI_UVT6	0.646 (-0.028)	61.113 (7.333)	10.418 (-0.241)	25.677 (0.354)	1.237 (-0.083)	1.679 (-0.085)	2.916 (-0.169)	0.138 (-0.005)
RNDG_ERA5_UVT6	0.662 (-0.012)	60.828 (7.048)	10.664 (-0.005)	25.761 (0.439)	1.248 (-0.072)	1.700 (-0.065)	2.948 (-0.137)	0.140 (-0.003)
RNDG_ERA5_UVT3	0.661 (-0.013)	60.270 (6.490)	10.524 (-0.135)	25.737 (0.415)	1.259 (-0.061)	1.694 (-0.071)	2.953 (-0.132)	0.141 (-0.002)
RNDG_ERA5_UVT1	0.660 (-0.014)	59.936 (6.156)	10.475 (-0.184)	25.714 (0.392)	1.264 (-0.056)	1.690 (-0.074)	2.954 (-0.130)	0.141 (-0.002)
Simulation	FNET	FSNT	FLNT	FLNTC	CRE	SWCF	LWCF	
unit	${\rm W}~{\rm m}^{-2}$	${\rm W}~{\rm m}^{-2}$	${\rm W}~{\rm m}^{-2}$	${\rm W}~{\rm m}^{-2}$	${\rm W}~{\rm m}^{-2}$	${\rm W}~{\rm m}^{-2}$	${\rm W}~{\rm m}^{-2}$	
CLIM	0.708 ± 0.786	239.924 ± 0.766	239.216 ± 0.132	263.264 ± 0.208	-24.929 ± 0.560	-48.977 ± 0.742	24.048 ± 0.189	
DNDG_ERAI_UV6	0.986 (0.278)	240.808 (0.884)	239.822 (0.607)	263.584 (0.320)	-24.608 (-0.321)	-48.369 (0.608)	23.761 (-0.287)	
RNDG_ERAI_UV6	0.598 (-0.111)	240.448 (0.524)	239.850 (0.635)	263.600 (0.336)	-24.916 (0.013)	-48.666 (0.312)	23.750 (-0.299)	
RNDG_ERA5_UV6	0.200 (-0.508)	239.676 (-0.248)	239.476 (0.260)	263.462 (0.198)	-25.457 (-0.528)	-49.443 (-0.466)	23.986 (-0.062)	
RNDG_ERA5_UV3	0.069 (-0.640)	239.604 (-0.320)	239.535 (0.320)	263.569 (0.306)	-25.477 (-0.548)	-49.511 (-0.534)	24.034 (-0.014)	
RNDG_ERA5_UV1	0.082 (-0.626)	239.627 (-0.297)	239.545 (0.329)	263.599 (0.335)	-25.435 (-0.506)	-49.489 (-0.511)	24.054 (-0.006)	
DNDG_ERAI_UVT6	0.783 (0.074)	241.430 (1.506)	240.647 (1.432)	262.364 (-0.900)	-25.822 (-0.893)	-47.539 (1.438)	21.717 (-2.331)	
RNDG_ERAI_UVT6	0.467 (-0.242)	240.010 (0.086)	239.543 (0.327)	261.889 (-1.375)	-26.581 (-1.652)	-48.927 (0.050)	22.346 (-1.702)	
RNDG_ERA5_UVT6	0.590 (-0.118)	239.499 (-0.424)	238.909 (-0.306)	261.457 (-1.807)	-26.782 (-1.853)	-49.329 (-0.352)	22.547 (-1.501)	
RNDG_ERA5_UVT3	0.455 (-0.253)	239.530 (-0.394)	239.074 (-0.141)	261.587 (-1.677)	-26.747 (-1.818)	-49.259 (-0.282)	22.512 (-1.536)	
RNDG_ERA5_UVT1	0.527 (-0.182)	239.689 (-0.235)	239.162 (-0.054)	261.643 (-1.621)	-26.601 (-1.672)	-49.082 (-0.105)	22.481 (-1.567)	

Table S3. As in Table S1 but for the aerosol induced changes (PD-PI differences, denoted by Δ). The aerosol effects are only checked for selected configurations. The detailed description can be referred to Table 1 and Section 2.3 in the main text. The result of CLIM simulation is given as the ensemble mean of global annual mean \pm one standard deviation of the 5 ensemble members See Table 1 and Section 2.3 in the main text for the detailed setups for each simulation.

Simulation	Δ CLDTOT	ΔLWP	Δ IWP	ΔTMQ	Δ PRECL	Δ PRECC	$\Delta PRECT$	$\Delta AODVIS$
unit	unitless	${ m g}~{ m m}^{-2}$	${ m g}~{ m m}^{-2}$	${\rm kg}{\rm m}^{-2}$	${\rm mm}~{\rm day}^{-1}$	${\rm mm}~{\rm day}^{-1}$	${\rm mm}~{\rm day}^{-1}$	unitless
CLIM	0.004 ± 0.002	2.133 ± 0.422	0.207 ± 0.037	0.065 ± 0.060	$\textbf{-0.008} \pm 0.009$	$\textbf{-0.019} \pm 0.006$	$\textbf{-0.028}\pm0.005$	0.031 ± 0.002
RNDG_UV6	0.005	2.316	0.217	0.098	-0.003	-0.025	-0.028	0.030
DNDG_UVT6	0.001	1.582	0.244	0.037	-0.006	-0.018	-0.024	0.030
RNDG_UVT6	0.001	1.693	0.224	0.036	-0.005	-0.017	-0.023	0.030
RNDG_UVT3	0.001	1.671	0.248	0.039	-0.005	-0.018	-0.024	0.030
RNDG_ERA5_UV6	0.005	2.509	0.231	0.128	-0.006	-0.023	-0.030	0.032
RNDG_ERA5_UVT6	0.001	2.256	0.078	0.032	-0.006	-0.016	-0.022	0.035
Simulation	Δ FNET	Δ FSNT	Δ FLNT	Δ FLNTC	ΔCRE	Δ SWCF	Δ LWCF	
unit	${\rm W}~{\rm m}^{-2}$	${\rm W}~{\rm m}^{-2}$	${\rm W}~{\rm m}^{-2}$	${\rm W}~{\rm m}^{-2}$	${\rm W}~{\rm m}^{-2}$	${\rm W}{\rm m}^{-2}$	${\rm W}~{\rm m}^{-2}$	
CLIM	$\textbf{-1.732}\pm0.166$	$\textbf{-2.419} \pm 0.120$	$\textbf{-0.686} \pm 0.110$	$\textbf{-0.062} \pm 0.085$	$\textbf{-1.036} \pm 0.088$	$\textbf{-1.660}\pm0.173$	0.624 ± 0.101	
RNDG_UV6	-1.733	-2.473	-0.740	-0.165	-1.222	-1.797	0.576	
DNDG_UVT6	-1.213	-1.856	-0.643	-0.027	-0.619	-1.235	0.616	
RNDG_UVT6	-1.325	-1.943	-0.618	-0.035	-0.736	-1.319	0.583	
RNDG_UVT3	-1.314	-1.988	-0.674	-0.037	-0.732	-1.369	0.636	
RNDG_ERA5_UV6	-1.655	-2.425	-0.770	-0.193	-1.206	-1.783	0.578	
RNDG_ERA5_UVT6	-1.459	-1.836	-0.377	-0.052	-0.834	-1.159	0.325	

Table S4. As in Table S3 but for the tropics region at 20° S – 20° N. See Table 1 and Section 2.3 in the main text for the detailed setups for each simulation.

Simulation	Δ CLDTOT	ΔLWP	Δ IWP	ΔTMQ	Δ PRECL	$\Delta PRECC$	$\Delta PRECT$	$\Delta AODVIS$
unit	unitless	${ m g~m}^{-2}$	${ m g~m^{-2}}$	${\rm kg}~{\rm m}^{-2}$	${\rm mm}~{\rm day}^{-1}$	${ m mm}~{ m day}^{-1}$	${\rm mm}~{\rm day}^{-1}$	unitless
CLIM	0.007 ± 0.001	0.933 ± 0.576	0.267 ± 0.076	0.212 ± 0.165	0.003 ± 0.013	$\textbf{-0.029} \pm 0.039$	$\textbf{-0.026} \pm 0.050$	0.038 ± 0.006
RNDG_UV6	0.006	0.816	0.272	0.179	-0.001	-0.041	-0.042	0.037
DNDG_UVT6	0.003	0.320	0.383	0.058	-0.003	-0.030	-0.033	0.037
RNDG_UVT6	0.002	0.419	0.345	0.059	-0.002	-0.029	-0.031	0.036
RNDG_UVT3	0.003	0.413	0.368	0.063	-0.002	-0.031	-0.033	0.036
RNDG_ERA5_UV6	0.007	0.901	0.242	0.223	-0.007	-0.040	-0.047	0.038
RNDG_ERA5_UVT6	0.000	0.680	0.026	0.052	-0.002	-0.028	-0.030	0.041
Simulation	Δ FNET	Δ FSNT	Δ FLNT	Δ FLNTC	ΔCRE	Δ SWCF	Δ LWCF	
unit	${\rm W~m^{-2}}$	${\rm W~m^{-2}}$	${\rm W~m^{-2}}$	${\rm W}~{\rm m}^{-2}$	${\rm W~m^{-2}}$	${\rm W}{\rm m}^{-2}$	${\rm W}~{\rm m}^{-2}$	
CLIM	$\textbf{-}1.802\pm0.384$	$\textbf{-2.784} \pm 0.443$	$\textbf{-0.982} \pm 0.090$	$\textbf{-0.212}\pm0.059$	$\textbf{-1.199}\pm0.393$	$\textbf{-1.969} \pm 0.439$	0.770 ± 0.078	
RNDG_UV6	-1.765	-2.657	-0.892	-0.191	-1.202	-1.903	0.701	
DNDG_UVT6	-1.207	-2.161	-0.954	-0.056	-0.522	-1.420	0.898	
RNDG_UVT6	-1.365	-2.260	-0.895	-0.062	-0.691	-1.523	0.833	
RNDG_UVT3	-1.377	-2.340	-0.962	-0.065	-0.700	-1.597	0.897	
RNDG_ERA5_UV6	-1.650	-2.472	-0.822	-0.226	-1.137	-1.733	0.596	
RNDG_ERA5_UVT6	-1.479	-1.824	-0.345	-0.083	-0.732	-0.994	0.263	



Figure S1. Anomaly correlation between the nudged simulations and the corresponding reanalysis (ERA-Interim or ERA5) for zonal wind (U), temperature (T) and specific humidity (Q): (a-c) annual mean spatial correlation; (d-f) spatially averaged temporal correlation. Different rows correspond to different nudged simulations. Different latitude bands are examined separately: polar regions $(60 - 90^{\circ}\text{S}, 60 - 90^{\circ}\text{N})$, midlatitudes $(30 - 60^{\circ}\text{S}, 30 - 60^{\circ}\text{N})$, and tropics $(20^{\circ}\text{S} - 20^{\circ}\text{N})$. The physical quantities at different pressure levels are indicated below the heat maps. All correlations were calculated from anomalies with respect to monthly averages: the ERAI-nudged simulations (labels contain "ERAI") are compared with ERA-Interim reanalysis, and the ERA5-nudged simulations (labels contain "ERA5") are compared with ERA5 reanalysis. The figure setups (color range and scale) are the same as those in Figure 5 in Sun et al. (2019) for the convenience of inter-comparison. The simulation setups are described in Section 2.3 and Table 1 of the main text.



Figure S2. Evaluation of the spatio-temporal distribution of daily precipitation from 1 June to 31 August 2010 over the tropical Pacific Ocean (10°S–10°N, 60°E–90°W, upper row) and North America (25°N–50°N, 150°E-60°W, lower row). (a) and (d): Hovmöller diagram of the meridionally averaged precipitation rates from TRMM. The dates are labeled along the y axis. (b–c) and (e–f): correlations between a Hovmöller diagram derived from TRMM and the Hovmöller diagram derived from various nudged simulations. Panels (b) and (e) compare simulations using ERA-Interim or ERA5 as constraining data and with or without temperature nudging. Panels (c) and (f) compare simulations with U,V or U, V, and T nudged towards ERA5 but using 6-hourly, 3-hourly, and hourly reanalysis for the constraining data. All nudged simulations shown here used the sequence of calculation in Fig. 1b, so the prefix "RNDG_" is dropped to keep the legends short. The simulation setups are described in Section 2.3 and Table 1 of the main text.



Figure S3. As in Figure S2 but the root-mean-square-errors (RMSEs) between a Hovmöller diagram derived from TRMM and the Hovmöller diagram derived from various nudged simulations are shown in panels (b–c) and (e–f). The simulation setups are described in Section 2.3 and Table 1 of the main text

References

Sun, J., Zhang, K., Wan, H., Ma, P.-L., Tang, Q., and Zhang, S.: Impact of Nudging Strategy on the Climate Representativeness and Hindcast Skill of Constrained EAMv1 Simulations, Journal of Advances in Modeling Earth Systems, 11, 3911–3933, https://doi.org/10.1029/2019MS001831, 2019.