



*Supplement of*

**Further improvement and evaluation of nudging in the E3SM Atmosphere Model version 1 (EAMv1): simulations of the mean climate, weather events, and anthropogenic aerosol effects**

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## Supplementary tables

For the physical quantities listed in Table S1, we present in Tables S2 and S3 the global and annual averages in the present-day (PD, year 2010) simulations performed with EAMv1 in the free-running mode and with various configurations of nudging. The experimental design is explained in Section 2.3 and Table 1 of the main text.

- 5 – Table S2 compares with the free-running configuration (CLIM) the various simulations nudged to EAMv1's own meterology. These nudged simulations are evaluated in Section 3 of the main text for their agreement with the free-running ensemble.
- Table S3 shows results from various simulations nudged to the ERA-Interim or ERA5 reanalysis. These simulations are evaluated in Section 4 for their mean climate and their ability to capture the observed weather events.
- 10 10 For the same physical quantities but a subset of the nudged simulations, we present in Tables S4 and S5 the differences between a pair of simulations conducted using PD or pre-industrial (PI, year 1850) emissions of anthropogenic aerosols and their precursors. In other words, the  $\Delta$  in Tables S4 and S5 denote the impacts of the anthropogenic aerosols.
- Table S4 shows the global averages.
- Table S5 show the averages over the tropics ( $20^{\circ}\text{S}$ - $20^{\circ}\text{N}$ ).
- 15 15 These simulations are evaluated in Section 5 of the main text for the agreements between the nudged and free-running simulations.

**Table S1.** List of physical quantities presented in Tables S2–S5.

Variable shortname	Physical quantity	Corresponding EAM output	Notes
CLDTOT	Total cloud fraction	CLDTOT	–
LWP	Total column integrated cloud liquid water path	TGCLDLWP	–
IWP	Total column integrated cloud ice water path	TGCLDIWP	–
TMQ	Vertically integrated total precipitable water	TMQ	–
AODVIS	Aerosol optical depth at 550 nm wavelength	AODVIS	–
PRECC	Large-scale precipitation rate	PRECC	–
PRECL	Convective precipitation rate	PRECL	–
PRECT	Total precipitation rate	PRECT	–
CRE <sub>SW</sub>	Shortwave cloud radiative effect	SWCF	CRE <sub>SW</sub> = SWCF
CRE <sub>LW</sub>	Longwave cloud radiative effect	LWCF	CRE <sub>LW</sub> = LWCF
$F_{SW}$	All-sky net downward shortwave flux at top of model	FSNT	$F_{SW,clear} = FSNT_C$
$F_{LW}$	All-sky net downward longwave flux at top of model	FLNT	$F_{LW} = -FLNT$
$F_{LW,clear}$	Clear-sky net downward longwave flux at top of model	FLNT <sub>C</sub>	$F_{LW,clear} = -FLNT_C$
CRE <sub>NET</sub>	Total cloud radiative effect	–	$F_{NET} = SWCF + LWCF$
$F_{NET}$	All-sky net radiative flux at top of model	–	$F_{NET} = FSNT - FLNT$

**Table S2.** Global annual averages in PD simulations. The nudged simulations were constrained by EAMv1's own meteorology. The results shown for CLIM are 1-year averages. The numbers in parentheses are the differences with respect to CLIM. The variable short names are explained in Table S1. The experimental design is explained in Table 1 and Section 2.3 of the main text.

Simulation	CLDTOT unitless	LWP $\text{g m}^{-2}$	IWP $\text{g m}^{-2}$	TMQ $\text{kg m}^{-2}$	PRECL $\text{mm day}^{-1}$	PRECC $\text{mm day}^{-1}$	PRECT $\text{mm day}^{-1}$	AODVIS 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	$F_{\text{NET}}$ $\text{W m}^{-2}$	$F_{\text{SW}}$ $\text{W m}^{-2}$	$F_{\text{LW}}$ $\text{W m}^{-2}$	$F_{\text{LW,clear}}$ $\text{W m}^{-2}$	$\text{CRE}_{\text{NET}}$ $\text{W m}^{-2}$	$\text{CRE}_{\text{SW}}$ $\text{W m}^{-2}$	$\text{CRE}_{\text{LW}}$ $\text{W m}^{-2}$	
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 S3.** As in Table S2 but for the simulations nudged to the ERA-Interim or ERA5 reanalysis. The results from CLIM are shown as the mean  $\pm$  one standard deviation of the 5 ensemble members. The numbers in parentheses are the differences with respect to the ensemble mean of CLIM. The variable short names are explained in Table S1. The experimental design is explained in Table 1 and Section 2.3 of the main text.

Simulation	CLDTOT unitless	LWP $\text{g m}^{-2}$	IWP $\text{g m}^{-2}$	TMQ $\text{kg m}^{-2}$	PRECL $\text{mm day}^{-1}$	PRECC $\text{mm day}^{-1}$	PRECT $\text{mm day}^{-1}$	AODVIS unitless
CLIM	0.674 $\pm$ 0.005	53.780 $\pm$ 0.819	10.659 $\pm$ 0.029	25.322 $\pm$ 0.132	1.320 $\pm$ 0.013	1.765 $\pm$ 0.003	3.084 $\pm$ 0.011	0.143 $\pm$ 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_ERAS_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_ERAS_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_ERAS_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_ERAS_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_ERAS_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_ERAS_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	$F_{\text{NET}}$ $\text{W m}^{-2}$	$F_{\text{SW}}$ $\text{W m}^{-2}$	$F_{\text{LW}}$ $\text{W m}^{-2}$	$F_{\text{LW,clear}}$ $\text{W m}^{-2}$	$\text{CRE}_{\text{NET}}$ $\text{W m}^{-2}$	$\text{CRE}_{\text{SW}}$ $\text{W m}^{-2}$	$\text{CRE}_{\text{LW}}$ $\text{W m}^{-2}$	
CLIM	0.708 $\pm$ 0.786	239.924 $\pm$ 0.766	239.216 $\pm$ 0.132	263.264 $\pm$ 0.208	-24.929 $\pm$ 0.560	-48.977 $\pm$ 0.742	24.048 $\pm$ 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_ERAS_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_ERAS_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_ERAS_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_ERAS_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_ERAS_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_ERAS_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 S4.** Aerosol-induced changes (PD-PI differences, denoted by  $\Delta$ ) in the global and annual averages of the physical quantities listed in Table S1. The CLIM results are given as the mean  $\pm$  one standard deviation of the 5 ensemble members.

Simulation	$\Delta\text{CLDTOT}$ unitless	$\Delta\text{LWP}$ $\text{g m}^{-2}$	$\Delta\text{IWP}$ $\text{g m}^{-2}$	$\Delta\text{TMQ}$ $\text{kg m}^{-2}$	$\Delta\text{PRECL}$ $\text{mm day}^{-1}$	$\Delta\text{PRECC}$ $\text{mm day}^{-1}$	$\Delta\text{PRECT}$ $\text{mm day}^{-1}$	$\Delta\text{AODVIS}$ unitless
CLIM	$0.004 \pm 0.002$	$2.133 \pm 0.422$	$0.207 \pm 0.037$	$0.065 \pm 0.060$	$-0.008 \pm 0.009$	$-0.019 \pm 0.006$	$-0.028 \pm 0.005$	$0.031 \pm 0.002$
RNDG_UV6	0.005	2.316	0.217	0.098	-0.003	-0.025	-0.028	0.030
RNDG_UV3	0.005	2.348	0.224	0.099	-0.004	-0.024	-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_UV3	0.005	2.525	0.226	0.124	-0.005	-0.024	-0.029	0.032
RNDG ERA5_UVT6	0.001	2.256	0.078	0.032	-0.006	-0.016	-0.022	0.035
RNDG ERA5_UVT3	0.001	2.274	0.087	0.033	-0.006	-0.015	-0.021	0.035
Simulation	$\Delta F_{\text{NET}}$ $\text{W m}^{-2}$	$\Delta F_{\text{SW}}$ $\text{W m}^{-2}$	$\Delta F_{\text{LW}}$ $\text{W m}^{-2}$	$\Delta F_{\text{LW,clear}}$ $\text{W m}^{-2}$	$\Delta\text{CRE}_{\text{NET}}$ $\text{W m}^{-2}$	$\Delta\text{CRE}_{\text{SW}}$ $\text{W m}^{-2}$	$\Delta\text{CRE}_{\text{LW}}$ $\text{W m}^{-2}$	
CLIM	$-1.732 \pm 0.166$	$-2.419 \pm 0.120$	$0.686 \pm 0.110$	$0.062 \pm 0.085$	$-1.036 \pm 0.088$	$-1.660 \pm 0.173$	$0.624 \pm 0.101$	
RNDG_UV6	-1.733	-2.473	0.740	0.165	-1.222	-1.797	0.576	
RNDG_UV3	-1.730	-2.479	0.750	0.169	-1.229	-1.809	0.580	
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_UV3	-1.660	-2.437	0.776	0.193	-1.207	-1.791	0.583	
RNDG ERA5_UVT6	-1.459	-1.836	0.377	0.052	-0.834	-1.159	0.325	
RNDG ERA5_UVT3	-1.473	-1.861	0.388	0.055	-0.855	-1.189	0.334	

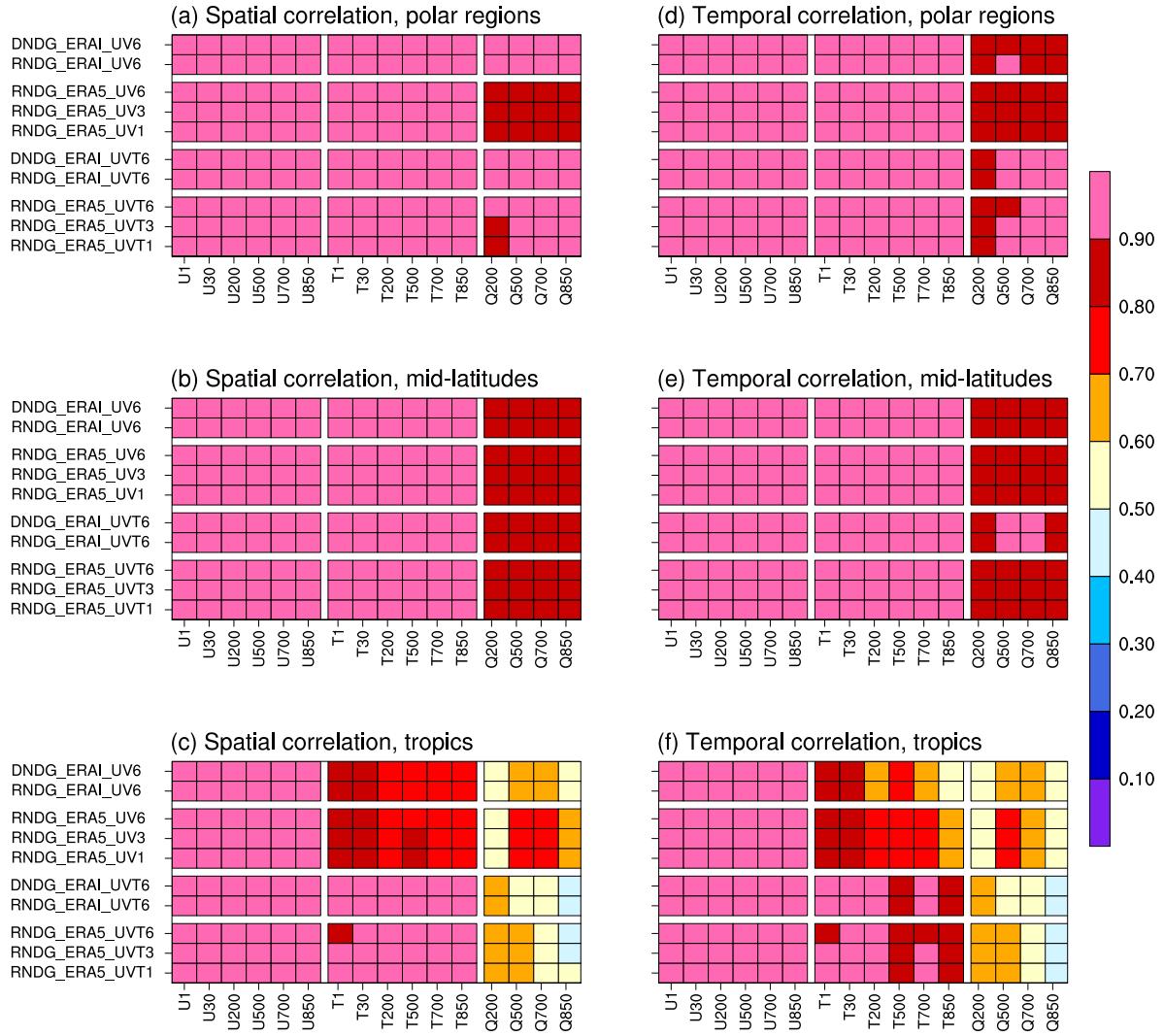
**Table S5.** As in Table S4 but for the averages over the tropics ( $20^{\circ}\text{S}$ – $20^{\circ}\text{N}$ ).

Simulation	$\Delta\text{CLDTOT}$ unitless	$\Delta\text{LWP}$ $\text{g m}^{-2}$	$\Delta\text{IWP}$ $\text{g m}^{-2}$	$\Delta\text{TMQ}$ $\text{kg m}^{-2}$	$\Delta\text{PRECL}$ $\text{mm day}^{-1}$	$\Delta\text{PRECC}$ $\text{mm day}^{-1}$	$\Delta\text{PRECT}$ $\text{mm day}^{-1}$	$\Delta\text{AODVIS}$ unitless
CLIM	$0.007 \pm 0.001$	$0.933 \pm 0.576$	$0.267 \pm 0.076$	$0.212 \pm 0.165$	$0.003 \pm 0.013$	$-0.029 \pm 0.039$	$-0.026 \pm 0.050$	$0.038 \pm 0.006$
RNDG_UV6	0.006	0.816	0.272	0.179	-0.001	-0.041	-0.042	0.037
RNDG_UV3	0.006	0.856	0.282	0.184	-0.003	-0.040	-0.044	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_UV3	0.007	0.870	0.235	0.217	-0.004	-0.042	-0.046	0.038
RNDG_ERA5_UVT6	0.0005	0.680	0.026	0.052	-0.002	-0.028	-0.030	0.041
RNDG_ERA5_UVT3	0.0005	0.706	0.036	0.054	-0.002	-0.027	-0.030	0.042
Simulation	$\Delta F_{\text{NET}}$ $\text{W m}^{-2}$	$\Delta F_{\text{SW}}$ $\text{W m}^{-2}$	$\Delta F_{\text{LW}}$ $\text{W m}^{-2}$	$\Delta F_{\text{LW,clear}}$ $\text{W m}^{-2}$	$\Delta\text{CRE}_{\text{NET}}$ $\text{W m}^{-2}$	$\Delta\text{CRE}_{\text{SW}}$ $\text{W m}^{-2}$	$\Delta\text{CRE}_{\text{LW}}$ $\text{W m}^{-2}$	
CLIM	$-1.802 \pm 0.384$	$-2.784 \pm 0.443$	$0.982 \pm 0.090$	$0.212 \pm 0.059$	$-1.199 \pm 0.393$	$-1.969 \pm 0.439$	$0.770 \pm 0.078$	
RNDG_UV6	-1.765	-2.657	0.892	0.191	-1.202	-1.903	0.701	
RNDG_UV3	-1.778	-2.694	0.916	0.201	-1.231	-1.946	0.715	
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_UV3	-1.636	-2.453	0.818	0.223	-1.118	-1.713	0.595	
RNDG_ERA5_UVT6	-1.479	-1.824	0.345	0.083	-0.732	-0.994	0.263	
RNDG_ERA5_UVT3	-1.502	-1.862	0.359	0.087	-0.756	-1.029	0.273	

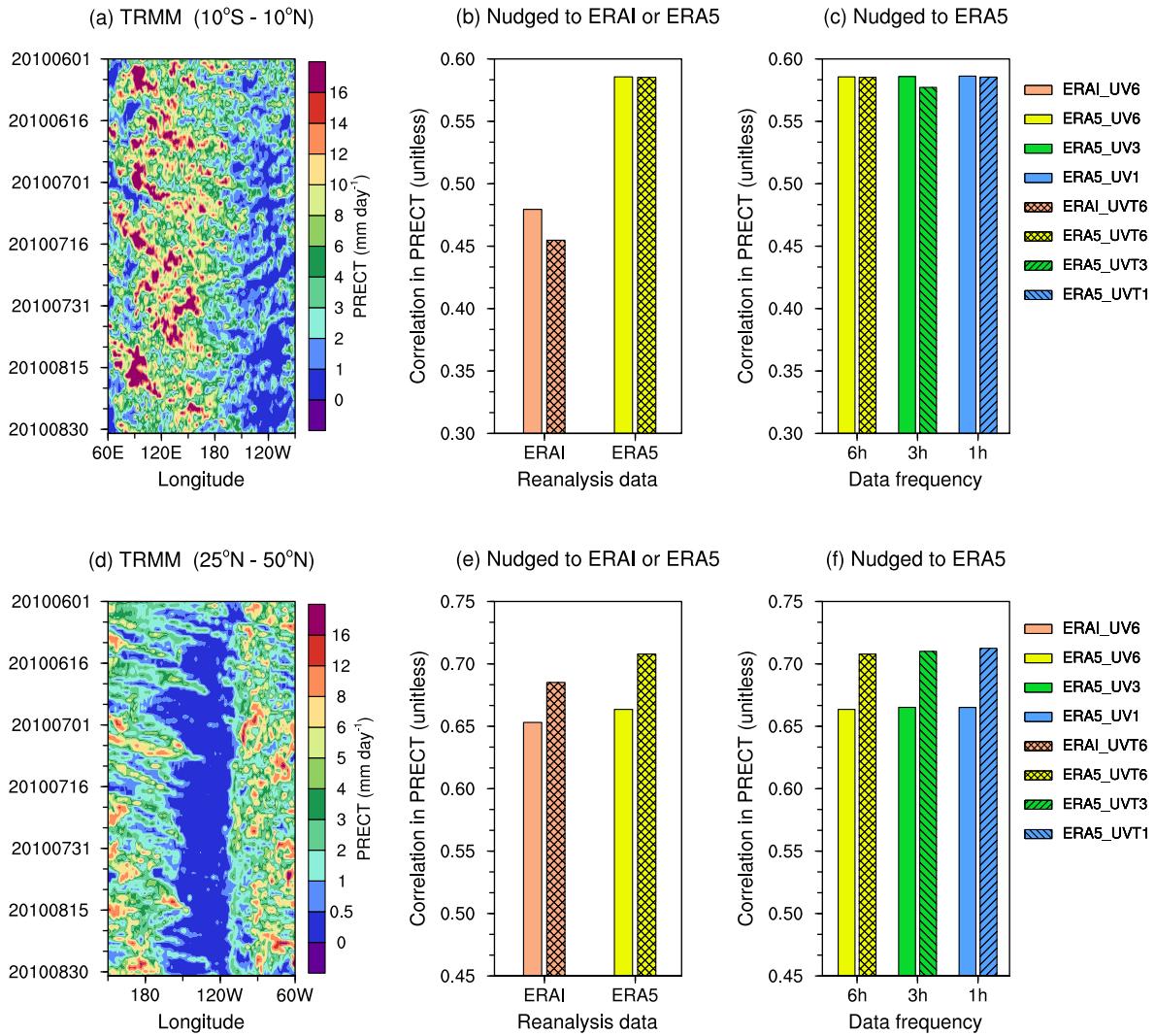
## **Supplementary figures**

The supplementary figures in this section show the anomaly correlations between nudged EAMv1 simulations and reanalysis data (ERA5 and ERA-Interim, Figure S1) and comparisons of daily precipitation between nudged EAMv1 simulations and

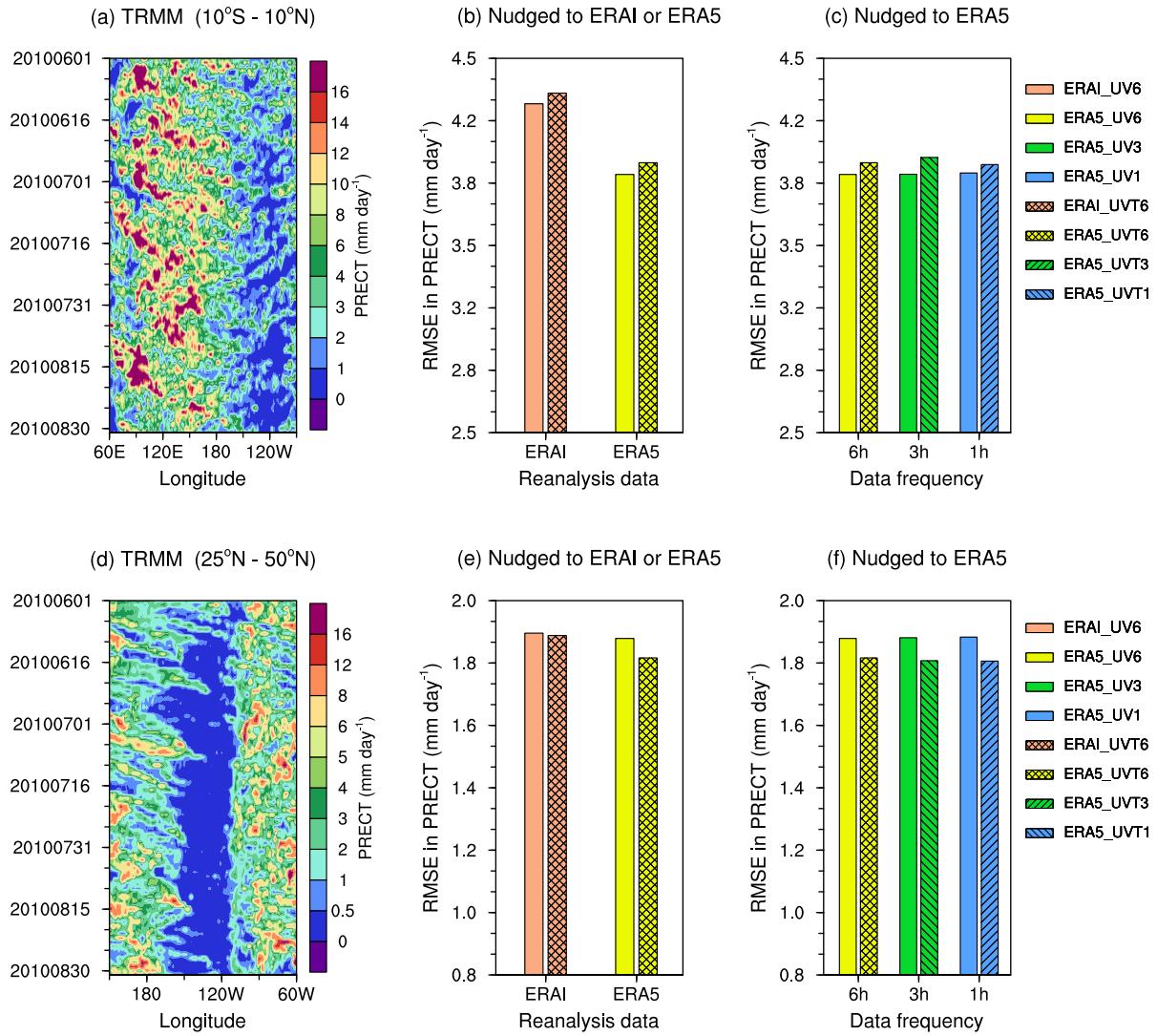
20 TRMM satellite observations from 1 June to 31 August 2010 (Figures S2 and S3).



**Figure S1.** Anomaly correlation between nudged PD simulations of the year 2010 and the corresponding reanalysis (ERA-Interim or ERA5) for zonal wind (U), temperature (T) and specific humidity (Q): left column: annual mean spatial correlation; right column: spatially averaged temporal correlation. Different rows of panels correspond to different latitude bands: top row: the Polar Regions ( $60 - 90^{\circ}$ S,  $60 - 90^{\circ}$ N); middle row: mid-latitudes ( $30 - 60^{\circ}$ S,  $30 - 60^{\circ}$ N); bottom row: the tropics ( $20^{\circ}$ S –  $20^{\circ}$ N). All correlations were calculated from anomalies with respect to monthly averages. The ERA-Iterim-nudged simulations (labels containing “ERAI”) are compared with the ERA-Interim reanalysis. The ERA5-nudged simulations (labels containing “ERA5”) are compared with ERA5 reanalysis. 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 ( $10^{\circ}\text{S}$ - $10^{\circ}\text{N}$ ,  $60^{\circ}\text{E}$ - $90^{\circ}\text{W}$ , upper row) and North Hemisphere midlatitude region ( $25^{\circ}\text{N}$ - $50^{\circ}\text{N}$ ,  $150^{\circ}\text{E}$ - $60^{\circ}\text{W}$ , 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 the Hovmöller diagram derived from TRMM and various Hovmöller diagrams derived from nudged simulations. All nudged simulations shown here used the sequence of calculations 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 panels (b–c) and (e–f) show the root-mean-square errors (RMSEs) instead of correlations.