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 |
|-------------|---------|-------|-------|-------|--------|--------|--------|--------|
|             | unitless| g m⁻² | g m⁻² | kg m⁻²| mm day⁻¹| mm day⁻¹| mm 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    | W m⁻² | W m⁻² | W m⁻² | W m⁻²   | W m⁻² | 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 (-1.03) | 263.438 (-1.154) | -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 ± 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 unit | LWP g m⁻² | IWP g m⁻² | TMQ kg m⁻² | PRECL mm day⁻¹ | PRECC mm day⁻¹ | PRECT mm day⁻¹ | AODVIS 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            | 0.664 (-0.011) | 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_UV3            | 0.664 (-0.010) | 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           | 0.661 (-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_UVT3           | 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 W m⁻² | FSNT W m⁻² | FLNT W m⁻² | FLNTC W m⁻² | CRE W m⁻² | SWCF W m⁻² | LWCF W 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            | 0.099 (-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_EERA5_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 (-1.141) | 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 \(\Delta\)). 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     | \(\Delta\text{CLDTOT}\) | \(\Delta\text{LWP}\) | \(\Delta\text{IWP}\) | \(\Delta\text{TMQ}\) | \(\Delta\text{PRECL}\) | \(\Delta\text{PRECC}\) | \(\Delta\text{PRECT}\) | \(\Delta\text{AODVIS}\) |
|---------------|-------------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| unit          | unitless                | g m\(^{-2}\)         | g m\(^{-2}\)         | kg m\(^{-2}\)        | mm day\(^{-1}\)      | mm day\(^{-1}\)      | mm day\(^{-1}\)      | 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                |
| 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     | \(\Delta F\text{NET}\) | \(\Delta F\text{SNT}\) | \(\Delta F\text{LNT}\) | \(\Delta F\text{LNTC}\) | \(\Delta C\text{RE}\) | \(\Delta S\text{WCF}\) | \(\Delta L\text{WCF}\) |
|---------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| unit          | W m\(^{-2}\)           | W m\(^{-2}\)           | W m\(^{-2}\)           | W m\(^{-2}\)           | W m\(^{-2}\)           | W m\(^{-2}\)           | 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                 |
| 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 $20^\circ$S – $20^\circ$N. See Table 1 and Section 2.3 in the main text for the detailed setups for each simulation.

| Simulation      | $\Delta$CLDTOT | $\Delta$LWP | $\Delta$IWP | $\Delta$TMQ | $\Delta$PRECL | $\Delta$PRECC | $\Delta$PRECT | $\Delta$AODVIS |
|-----------------|-----------------|-------------|-------------|-------------|--------------|-------------|--------------|---------------|
| unit            | unitless        | g m$^{-2}$  | g m$^{-2}$  | kg m$^{-2}$ | mm day$^{-1}$| mm day$^{-1}$| mm day$^{-1}$| unitless      |
| CLIM            | 0.007 ± 0.001   | 0.933 ± 0.576 | 0.267 ± 0.076 | 0.212 ± 0.165 | 0.003 ± 0.013 | -0.029 ± 0.039 | -0.026 ± 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      | $\Delta$FNET  | $\Delta$FSNT | $\Delta$FLNT | $\Delta$FLNTC | $\Delta$CRE | $\Delta$SWCF | $\Delta$LWCF |
|-----------------|----------------|-------------|-------------|-------------|-------------|-------------|-------------|
| unit            | W m$^{-2}$     | W m$^{-2}$  | W m$^{-2}$  | W m$^{-2}$  | W m$^{-2}$  | W m$^{-2}$  | W m$^{-2}$  |
| CLIM            | -1.802 ± 0.384 | -2.784 ± 0.443 | -0.982 ± 0.090 | -0.212 ± 0.059 | -1.199 ± 0.393 | -1.969 ± 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°S, 60 – 90°N), midlatitudes (30 – 60°S, 30 – 60°N), and tropics (20°S – 20°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.