

1 **Table S1: TOA ERF (Wm^{-2}), ΔTs (K), $\Delta\text{Ts}/\text{ERF}$ (K·(Wm^{-2}) $^{-1}$), $\Delta\text{SWV}_{\text{slow}}$ (ppmv), $\Delta\text{SWV}_{\text{slow}}/\text{ERF}$ (ppmv·(Wm^{-2}) $^{-1}$), $\Delta\text{SWV}_{\text{fast}}$ (ppmv), and $\Delta\text{SWV}_{\text{fast}}/\text{ERF}$ (ppmv·(Wm^{-2}) $^{-1}$) from all models and perturbations and ensemble average.**

| 2xCO ₂ | ERF | ΔTs | $\Delta\text{Ts}/\text{ERF}$ | $\Delta\text{SWV}_{\text{slow}}$ | | | $\Delta\text{SWV}_{\text{slow}}/\text{ERF}$ | | | $\Delta\text{SWV}_{\text{fast}}$ | | | $\Delta\text{SWV}_{\text{fast}}/\text{ERF}$ | | |
|-------------------|------|-------------------|------------------------------|----------------------------------|--------|--------|---|--------|--------|----------------------------------|--------|--------|---|--------|--------|
| | | | | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS |
| CAM4 | 3.57 | 3.15 | 0.88 | 0.81 | 8.29 | 4.53 | 0.23 | 2.33 | 1.27 | -0.02 | 1.16 | -0.01 | -0.01 | 0.33 | -0.00 |
| CAM5 | 4.00 | 3.83 | 0.96 | 1.17 | 8.29 | 4.72 | 0.29 | 2.07 | 1.18 | 0.07 | 1.76 | 0.06 | 0.02 | 0.44 | 0.02 |
| HadGEM3 | 3.64 | 8.02 | 2.20 | 7.15 | 33.63 | 19.87 | 1.96 | 9.23 | 5.45 | 0.11 | 0.75 | -0.04 | 0.03 | 0.20 | -0.01 |
| HadGEM2 | 3.73 | 4.10 | 1.10 | 1.21 | 8.99 | 3.02 | 0.33 | 2.41 | 0.81 | 0.12 | 0.78 | -0.07 | 0.03 | 0.21 | -0.02 |
| CanESM2 | 3.57 | 3.97 | 1.11 | 0.94 | 11.26 | 4.57 | 0.26 | 3.15 | 1.28 | -0.23 | 0.48 | 0.13 | -0.07 | 0.13 | 0.04 |
| IPSL-CM5A | 3.36 | 3.83 | 1.14 | 2.05 | 9.80 | 5.86 | 0.61 | 2.91 | 1.74 | 0.28 | 0.62 | 0.29 | 0.08 | 0.18 | 0.09 |
| MPI-ESM | 4.14 | 2.20 | 0.53 | 1.82 | 8.49 | 3.87 | 0.44 | 2.05 | 0.93 | 0.29 | 1.03 | -0.05 | 0.07 | 0.25 | -0.01 |
| GISS | 3.99 | 2.12 | 0.53 | 0.49 | 2.29 | 1.51 | 0.12 | 0.57 | 0.38 | -0.09 | -0.18 | -0.14 | -0.02 | -0.04 | -0.04 |
| MIROC-SPRINTARS | 3.62 | 1.47 | 0.40 | 0.30 | 4.16 | 2.91 | 0.08 | 1.15 | 0.80 | -0.17 | 0.52 | -0.02 | -0.05 | 0.14 | -0.01 |
| ensemble average | 3.74 | 3.63 | 0.98 | 1.77 | 10.58 | 5.65 | 0.48 | 2.87 | 1.54 | 0.04 | 0.77 | 0.02 | 0.01 | 0.20 | 0.01 |

| 3xCH4 | ERF | ΔTs | $\Delta\text{Ts}/\text{ERF}$ | $\Delta\text{SWV}_{\text{slow}}$ | | | $\Delta\text{SWV}_{\text{slow}}/\text{ERF}$ | | | $\Delta\text{SWV}_{\text{fast}}$ | | | $\Delta\text{SWV}_{\text{fast}}/\text{ERF}$ | | |
|------------------|------|-------------------|------------------------------|----------------------------------|--------|--------|---|--------|--------|----------------------------------|--------|--------|---|--------|--------|
| | | | | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS |
| CAM4 | 1.23 | 1.07 | 0.87 | 0.33 | 2.47 | 1.55 | 0.27 | 2.01 | 1.25 | -0.01 | -0.01 | 0.01 | -0.01 | -0.01 | 0.00 |
| CAM5 | 0.96 | 0.73 | 0.76 | 0.34 | 1.46 | 0.83 | 0.35 | 1.51 | 0.87 | 0.24 | 0.25 | 0.40 | 0.25 | 0.26 | 0.42 |
| HadGEM3 | 1.39 | 2.37 | 1.70 | 1.71 | 7.98 | 4.86 | 1.23 | 5.72 | 3.49 | 0.16 | 0.35 | 0.05 | 0.12 | 0.25 | 0.04 |
| HadGEM2 | 1.25 | 1.43 | 1.14 | 0.37 | 2.62 | 0.92 | 0.29 | 2.10 | 0.74 | 0.17 | 0.27 | 0.03 | 0.13 | 0.22 | 0.03 |
| CanESM2 | 1.36 | 0.78 | 0.58 | -0.01 | 1.71 | 0.57 | -0.01 | 1.26 | 0.42 | 0.31 | 0.83 | 0.21 | 0.23 | 0.61 | 0.15 |
| IPSL-CM5A | 1.63 | 1.50 | 0.92 | 0.38 | 3.21 | 1.96 | 0.24 | 1.97 | 1.21 | 0.09 | 0.24 | 0.02 | 0.06 | 0.15 | 0.01 |
| MPI-ESM | 0.95 | 0.58 | 0.61 | 0.37 | 1.80 | 0.54 | 0.38 | 1.90 | 0.57 | 0.28 | 0.51 | 0.30 | 0.29 | 0.54 | 0.32 |
| GISS | 1.34 | 0.42 | 0.32 | 0.11 | 0.43 | 0.41 | 0.08 | 0.32 | 0.31 | -0.05 | -0.26 | -0.37 | -0.04 | -0.19 | -0.28 |
| MIROC-SPRINTARS | 0.78 | 0.28 | 0.35 | 0.00 | 0.81 | 0.55 | 0.00 | 1.04 | 0.70 | 0.34 | 0.34 | 0.32 | 0.43 | 0.44 | 0.41 |
| ensemble average | 1.21 | 1.02 | 0.81 | 0.40 | 2.50 | 1.36 | 0.32 | 1.98 | 1.06 | 0.17 | 0.28 | 0.11 | 0.16 | 0.25 | 0.12 |

| 2%Solar | ERF | ΔTs | $\Delta\text{Ts}/\text{ERF}$ | $\Delta\text{SWV}_{\text{slow}}$ | | | $\Delta\text{SWV}_{\text{slow}}/\text{ERF}$ | | | $\Delta\text{SWV}_{\text{fast}}$ | | | $\Delta\text{SWV}_{\text{fast}}/\text{ERF}$ | | |
|-----------|------|-------------------|------------------------------|----------------------------------|--------|--------|---|--------|--------|----------------------------------|--------|--------|---|--------|--------|
| | | | | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS |
| CAM4 | 3.95 | 2.83 | 0.72 | 0.91 | 7.83 | 4.92 | 0.23 | 1.98 | 1.24 | 0.16 | 1.59 | 0.20 | 0.04 | 0.40 | 0.05 |
| CAM5 | 4.32 | 3.54 | 0.82 | 1.20 | 9.11 | 5.30 | 0.28 | 2.11 | 1.23 | 0.19 | 1.46 | 0.30 | 0.04 | 0.34 | 0.07 |
| HadGEM3 | 4.36 | 9.65 | 2.21 | 9.34 | 46.76 | 27.55 | 2.14 | 10.73 | 6.32 | 0.21 | 0.88 | 0.08 | 0.05 | 0.20 | 0.02 |
| HadGEM2 | 4.28 | 3.11 | 0.73 | 1.45 | 8.64 | 2.78 | 0.34 | 2.02 | 0.65 | 0.27 | 0.89 | 0.20 | 0.06 | 0.21 | 0.05 |
| CanESM2 | 4.09 | 3.02 | 0.74 | 1.43 | 13.34 | 5.06 | 0.35 | 3.26 | 1.24 | 0.22 | 1.11 | 0.37 | 0.05 | 0.27 | 0.09 |
| IPSL-CM5A | 4.11 | 4.49 | 1.09 | 3.33 | 13.07 | 7.36 | 0.81 | 3.18 | 1.79 | 0.23 | 0.76 | 0.32 | 0.06 | 0.19 | 0.08 |
| MPI-ESM | 4.12 | 2.81 | 0.68 | 1.64 | 9.17 | 3.51 | 0.40 | 2.23 | 0.85 | 0.45 | 1.43 | 0.52 | 0.11 | 0.35 | 0.13 |
| GISS | 4.48 | 1.85 | 0.41 | 0.52 | 2.21 | 1.67 | 0.12 | 0.49 | 0.37 | 0.09 | 0.39 | 0.17 | 0.02 | 0.09 | 0.04 |

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| | | | | | | | | | | | | | | | |
|------------------|------|------|------|------|-------|------|------|------|------|------|------|------|------|------|------|
| MIROC-SPRINTARS | 4.15 | 1.36 | 0.33 | 0.18 | 4.61 | 3.64 | 0.04 | 1.11 | 0.88 | 0.20 | 0.69 | 0.21 | 0.05 | 0.17 | 0.05 |
| ensemble average | 4.21 | 3.63 | 0.86 | 2.22 | 12.75 | 6.87 | 0.52 | 3.01 | 1.62 | 0.22 | 1.02 | 0.27 | 0.05 | 0.25 | 0.06 |

| 10xBC | ERF | ΔT_s | $\Delta T_s/ERF$ | ΔSWV_{slow} | | | $\Delta SWV_{slow}/ERF$ | | | ΔSWV_{fast} | | | $\Delta SWV_{fast}/ERF$ | | |
|------------------|------|--------------|------------------|---------------------|--------|--------|-------------------------|--------|--------|---------------------|--------|--------|-------------------------|--------|--------|
| | | | | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS |
| CAM4 | 0.77 | 0.43 | 0.55 | 0.06 | 2.40 | 0.54 | 0.08 | 3.12 | 0.70 | 0.63 | 3.33 | 0.76 | 0.82 | 4.32 | 0.99 |
| CAM5 | 0.43 | 0.38 | 0.89 | -0.10 | 1.07 | 0.06 | -0.24 | 2.48 | 0.15 | 0.66 | 2.49 | 0.55 | 1.52 | 5.77 | 1.28 |
| HadGEM3 | 0.70 | 1.19 | 1.72 | 1.05 | 5.86 | 2.20 | 1.51 | 8.44 | 3.17 | 0.47 | 0.80 | 0.14 | 0.68 | 1.15 | 0.20 |
| HadGEM2 | 3.17 | 2.14 | 0.68 | 1.62 | 6.09 | 1.44 | 0.51 | 1.92 | 0.46 | 3.27 | 5.58 | 0.93 | 1.03 | 1.76 | 0.30 |
| CanESM2 | 1.55 | 1.77 | 1.14 | -0.03 | 6.22 | 1.72 | -0.02 | 4.01 | 1.11 | 1.99 | 2.56 | 1.70 | 1.28 | 1.65 | 1.09 |
| IPSL-CM5A | 0.81 | 1.47 | 1.81 | 0.38 | 4.09 | 1.31 | 0.47 | 5.03 | 1.61 | 1.28 | 2.42 | 0.81 | 1.57 | 2.98 | 1.00 |
| GISS | 1.23 | 0.46 | 0.37 | 0.16 | 1.41 | 0.30 | 0.13 | 1.14 | 0.24 | 0.30 | 0.97 | 0.42 | 0.24 | 0.79 | 0.34 |
| MIROC-SPRINTARS | 0.63 | 0.13 | 0.20 | -0.06 | -0.04 | 0.37 | -0.10 | -0.06 | 0.59 | 0.28 | 0.97 | 0.15 | 0.44 | 1.54 | 0.24 |
| ensemble average | 1.16 | 1.00 | 0.92 | 0.38 | 3.39 | 0.99 | 0.29 | 3.26 | 1.00 | 1.11 | 2.39 | 0.68 | 0.95 | 2.50 | 0.68 |

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| 5xSO ₄ | ERF | ΔT_s | $\Delta T_s/ERF$ | ΔSWV_{slow} | | | $\Delta SWV_{slow}/ERF$ | | | ΔSWV_{fast} | | | $\Delta SWV_{fast}/ERF$ | | |
|-------------------|-------|--------------|------------------|---------------------|--------|--------|-------------------------|--------|--------|---------------------|--------|--------|-------------------------|--------|--------|
| | | | | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS |
| CAM4 | -2.16 | -1.49 | 0.69 | -0.37 | -3.33 | -1.37 | 0.17 | 1.54 | 0.64 | -0.01 | -1.12 | -0.09 | 0.00 | 0.52 | 0.04 |
| CAM5 | -2.10 | -1.79 | 0.85 | -0.27 | -4.25 | -2.41 | 0.13 | 2.02 | 1.15 | -0.07 | -0.06 | 0.50 | 0.03 | 0.03 | -0.24 |
| HadGEM3 | -8.26 | -6.70 | 0.81 | -3.85 | -15.69 | -11.99 | 0.47 | 1.90 | 1.45 | -0.10 | -1.03 | -0.09 | 0.01 | 0.12 | 0.01 |
| HadGEM2 | -3.84 | -5.06 | 1.32 | -1.53 | -5.69 | -1.51 | 0.40 | 1.48 | 0.39 | -0.54 | -1.00 | -0.13 | 0.14 | 0.26 | 0.03 |
| CanESM2 | -3.25 | -4.45 | 1.37 | -0.51 | -8.43 | -2.26 | 0.16 | 2.60 | 0.70 | -0.01 | -0.63 | -0.04 | 0.00 | 0.19 | 0.01 |
| IPSL-CM5A | -2.75 | -1.99 | 0.73 | -0.78 | -6.58 | -4.01 | 0.29 | 2.40 | 1.46 | 0.08 | -0.21 | 0.01 | -0.03 | 0.08 | -0.00 |
| GISS | -2.79 | -1.40 | 0.50 | -0.28 | -1.58 | -0.72 | 0.10 | 0.56 | 0.26 | 0.02 | -0.19 | 0.00 | -0.01 | 0.07 | -0.00 |
| MIROC-SPRINTARS | -2.77 | -2.12 | 0.77 | -0.32 | -3.85 | -1.71 | 0.11 | 1.39 | 0.62 | 0.01 | -0.66 | -0.09 | -0.00 | 0.24 | 0.03 |
| ensemble average | -3.49 | -3.13 | 0.88 | -0.99 | -6.18 | -3.25 | 0.23 | 1.74 | 0.83 | -0.08 | -0.61 | 0.01 | 0.02 | 0.19 | -0.01 |

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| 10xCFC12 | ERF | ΔT_s | $\Delta T_s/ERF$ | ΔSWV_{slow} | | | $\Delta SWV_{slow}/ERF$ | | | ΔSWV_{fast} | | | $\Delta SWV_{fast}/ERF$ | | |
|------------------|------|--------------|------------------|---------------------|--------|--------|-------------------------|--------|--------|---------------------|--------|--------|-------------------------|--------|--------|
| | | | | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS |
| CAM4 | 1.54 | 1.34 | 0.87 | 0.43 | 3.01 | 1.84 | 0.28 | 1.96 | 1.20 | 0.21 | 0.47 | 0.30 | 0.13 | 0.31 | 0.19 |
| CAM5 | 1.34 | 1.00 | 0.74 | 0.40 | 3.76 | 1.31 | 0.30 | 2.81 | 0.98 | 0.36 | 0.80 | 0.47 | 0.27 | 0.60 | 0.35 |
| HadGEM3 | 1.51 | 2.70 | 1.78 | 2.17 | 9.50 | 5.39 | 1.43 | 6.27 | 3.56 | 0.37 | 0.66 | 0.23 | 0.24 | 0.44 | 0.15 |
| HadGEM2 | 1.45 | 1.47 | 1.01 | 0.31 | 2.46 | 1.18 | 0.21 | 1.69 | 0.81 | 0.48 | 0.38 | 0.27 | 0.33 | 0.26 | 0.18 |
| GISS | 1.27 | 0.44 | 0.34 | 0.09 | 0.52 | 0.50 | 0.07 | 0.41 | 0.39 | 0.12 | 0.22 | 0.15 | 0.09 | 0.17 | 0.12 |
| MIROC-SPRINTARS | 1.20 | 0.48 | 0.40 | 0.07 | 1.27 | 0.86 | 0.06 | 1.06 | 0.72 | 0.32 | 0.42 | 0.15 | 0.27 | 0.35 | 0.13 |
| ensemble average | 1.39 | 1.24 | 0.86 | 0.58 | 3.42 | 1.85 | 0.39 | 2.37 | 1.28 | 0.31 | 0.49 | 0.26 | 0.22 | 0.35 | 0.19 |

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| 10xCFC11 | ERF | ΔT_s | $\Delta T_s/ERF$ | ΔSWV_{slow} | | | $\Delta SWV_{slow}/ERF$ | | | ΔSWV_{fast} | | | $\Delta SWV_{fast}/ERF$ | | |
|------------------|------|--------------|------------------|---------------------|-----------|-----------|-------------------------|-----------|-----------|---------------------|-----------|-----------|-------------------------|-----------|-----------|
| | | | | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS |
| HadGEM2 | 1.20 | 1.43 | 1.20 | 0.69 | 3.24 | 0.85 | 0.58 | 2.70 | 0.71 | 0.37 | 0.34 | 0.24 | 0.31 | 0.29 | 0.20 |
| MIROC-SPRINTARS | 1.15 | 0.44 | 0.38 | 0.15 | 1.69 | 1.12 | 0.13 | 1.47 | 0.98 | 0.29 | 0.16 | 0.38 | 0.25 | 0.14 | 0.33 |
| ensemble average | 1.21 | 0.94 | 0.79 | 0.42 | 2.47 | 0.99 | 0.35 | 2.09 | 0.84 | 0.33 | 0.25 | 0.31 | 0.28 | 0.21 | 0.26 |

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| 3xN ₂ O | ERF | ΔT_s | $\Delta T_s/ERF$ | ΔSWV_{slow} | | | $\Delta SWV_{slow}/ERF$ | | | ΔSWV_{fast} | | | $\Delta SWV_{fast}/ERF$ | | |
|--------------------|------|--------------|------------------|---------------------|-----------|-----------|-------------------------|-----------|-----------|---------------------|-----------|-----------|-------------------------|-----------|-----------|
| | | | | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS |
| CAM4 | 1.42 | 1.09 | 0.77 | 0.32 | 2.53 | 1.65 | 0.23 | 1.79 | 1.17 | -0.00 | 0.17 | -0.09 | -0.00 | 0.12 | -0.06 |
| HadGEM2 | 2.19 | 1.46 | 0.67 | 0.73 | 3.58 | 1.47 | 0.33 | 1.63 | 0.67 | 0.43 | 0.40 | 0.26 | 0.20 | 0.18 | 0.12 |
| MIROC-SPRINTARS | 1.42 | 0.57 | 0.40 | 0.13 | 1.54 | 1.55 | 0.09 | 1.08 | 1.09 | 0.04 | -0.00 | -0.38 | 0.03 | -0.00 | -0.27 |
| ensemble average | 1.68 | 1.04 | 0.61 | 0.39 | 2.55 | 1.56 | 0.22 | 1.50 | 0.97 | 0.16 | 0.19 | -0.07 | 0.08 | 0.10 | -0.07 |

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| 5xO ₃ | ERF | ΔT_s | $\Delta T_s/ERF$ | ΔSWV_{slow} | | | $\Delta SWV_{slow}/ERF$ | | | ΔSWV_{fast} | | | $\Delta SWV_{fast}/ERF$ | | |
|------------------|------|--------------|------------------|---------------------|-----------|-----------|-------------------------|-----------|-----------|---------------------|-----------|-----------|-------------------------|-----------|-----------|
| | | | | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS |
| MIROC-SPRINTARS | 3.46 | 1.22 | 0.35 | 0.19 | 2.73 | 2.04 | 0.06 | 0.79 | 0.59 | 0.67 | 2.16 | 2.96 | 0.19 | 0.62 | 0.86 |

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| 10xBCTAU | ERF | ΔT_s | $\Delta T_s/ERF$ | ΔSWV_{slow} | | | $\Delta SWV_{slow}/ERF$ | | | ΔSWV_{fast} | | | $\Delta SWV_{fast}/ERF$ | | |
|------------------|------|--------------|------------------|---------------------|--------|--------|-------------------------|--------|--------|---------------------|--------|--------|-------------------------|--------|--------|
| | | | | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS | TLS | NH LMS | SH LMS |
| CAM4 | 0.65 | 0.26 | 0.41 | 0.03 | 0.89 | 0.39 | 0.05 | 1.37 | 0.60 | 0.17 | 1.29 | 0.25 | 0.25 | 1.99 | 0.39 |
| GISS | 1.22 | 0.41 | 0.34 | 0.09 | 0.79 | 0.30 | 0.07 | 0.65 | 0.25 | 0.07 | 0.26 | 0.10 | 0.06 | 0.21 | 0.09 |
| ensemble average | 0.93 | 0.34 | 0.37 | 0.06 | 0.84 | 0.35 | 0.06 | 1.01 | 0.42 | 0.12 | 0.78 | 0.18 | 0.16 | 1.10 | 0.24 |

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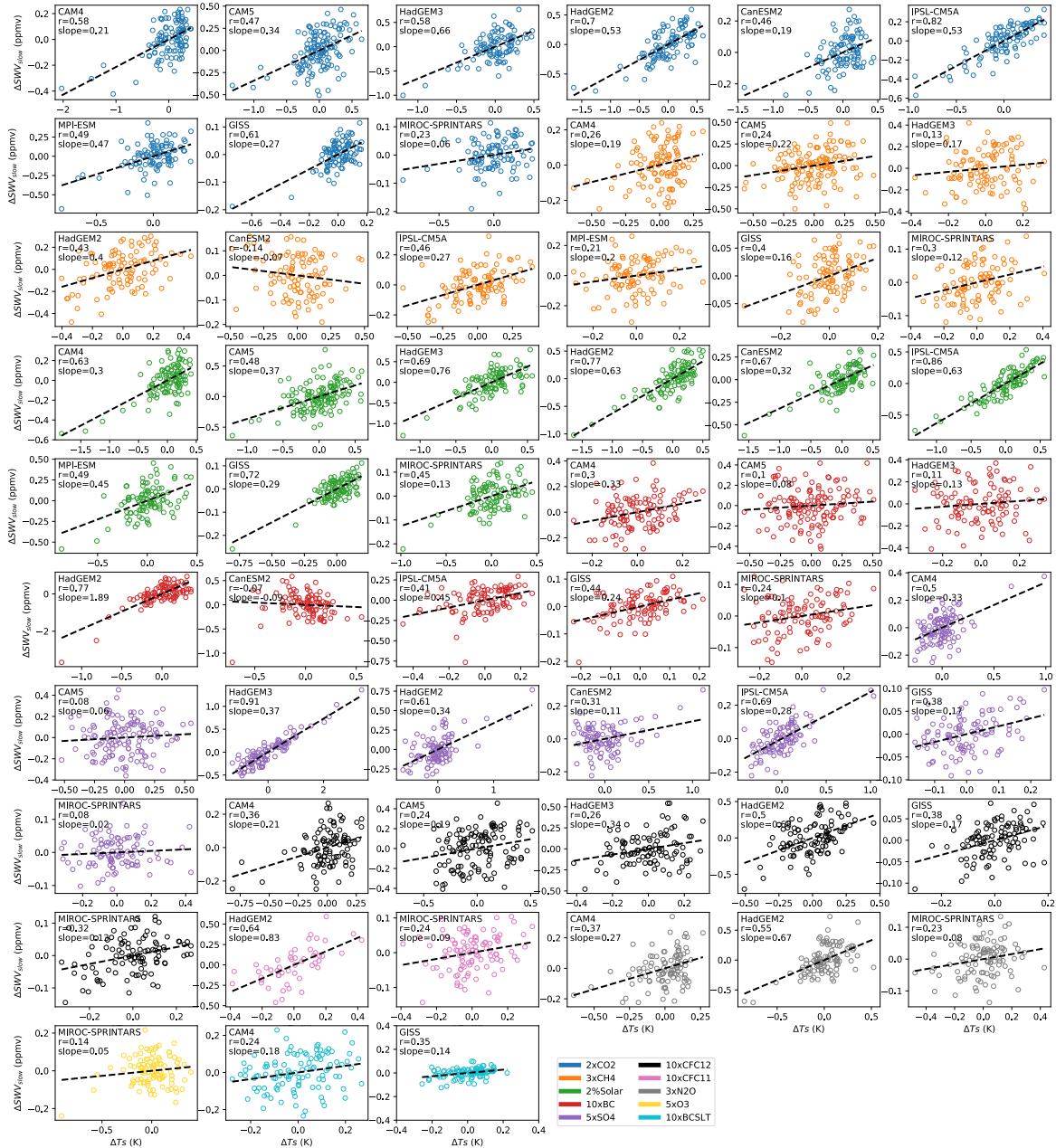


Figure S1. Linear regression between the annual mean time series of ΔSWV_{slow} (ppmv) in the TLS and the annual mean global averaged ΔTs (K) time series. In each panel, the circles are annual mean results, and the dashed line is the linear fit. The color coding indicates results from different perturbations.

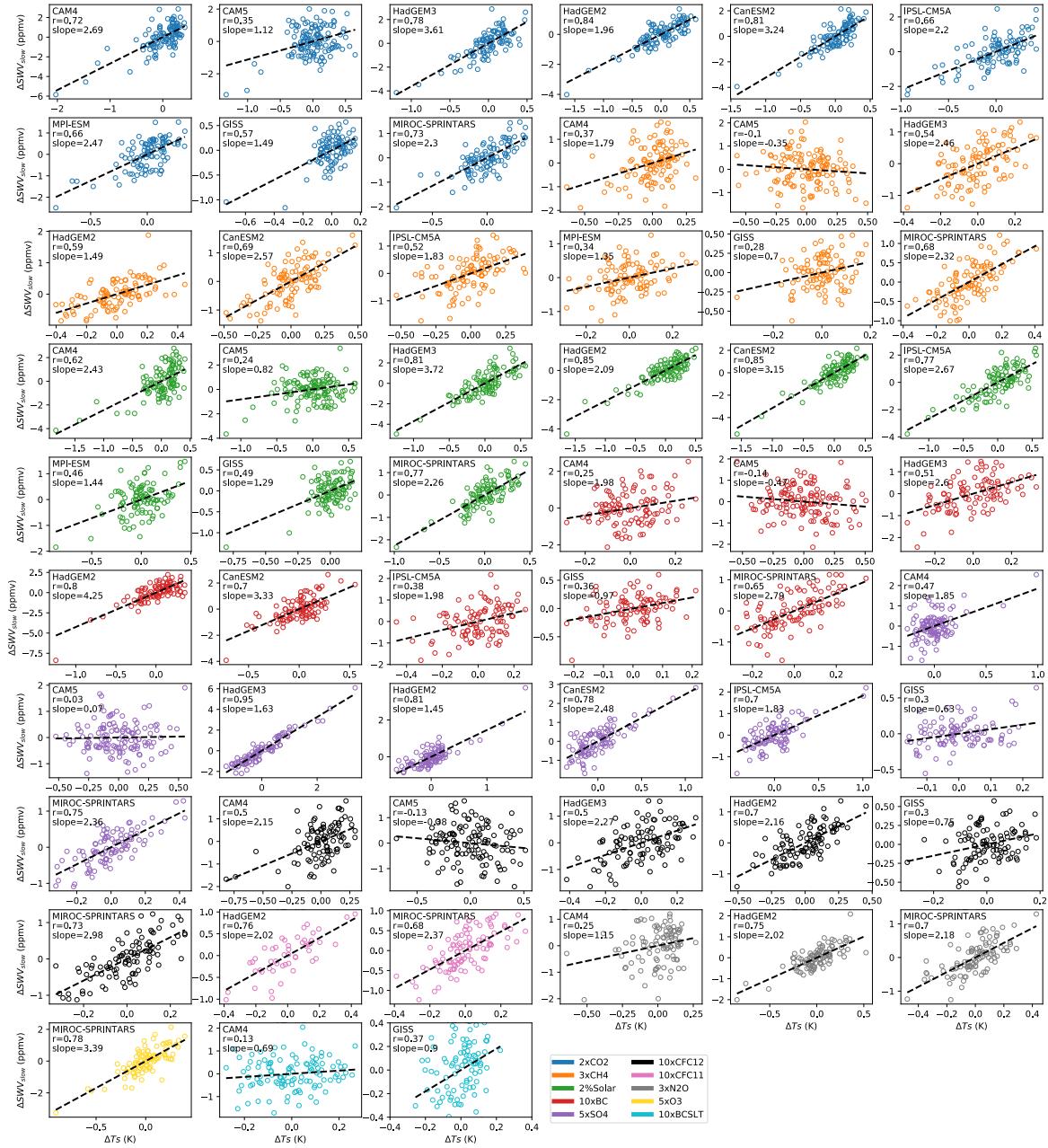


Figure S2. Same as Figure S1, but for ΔSWV_{slow} (ppmv) in the NH LMS.

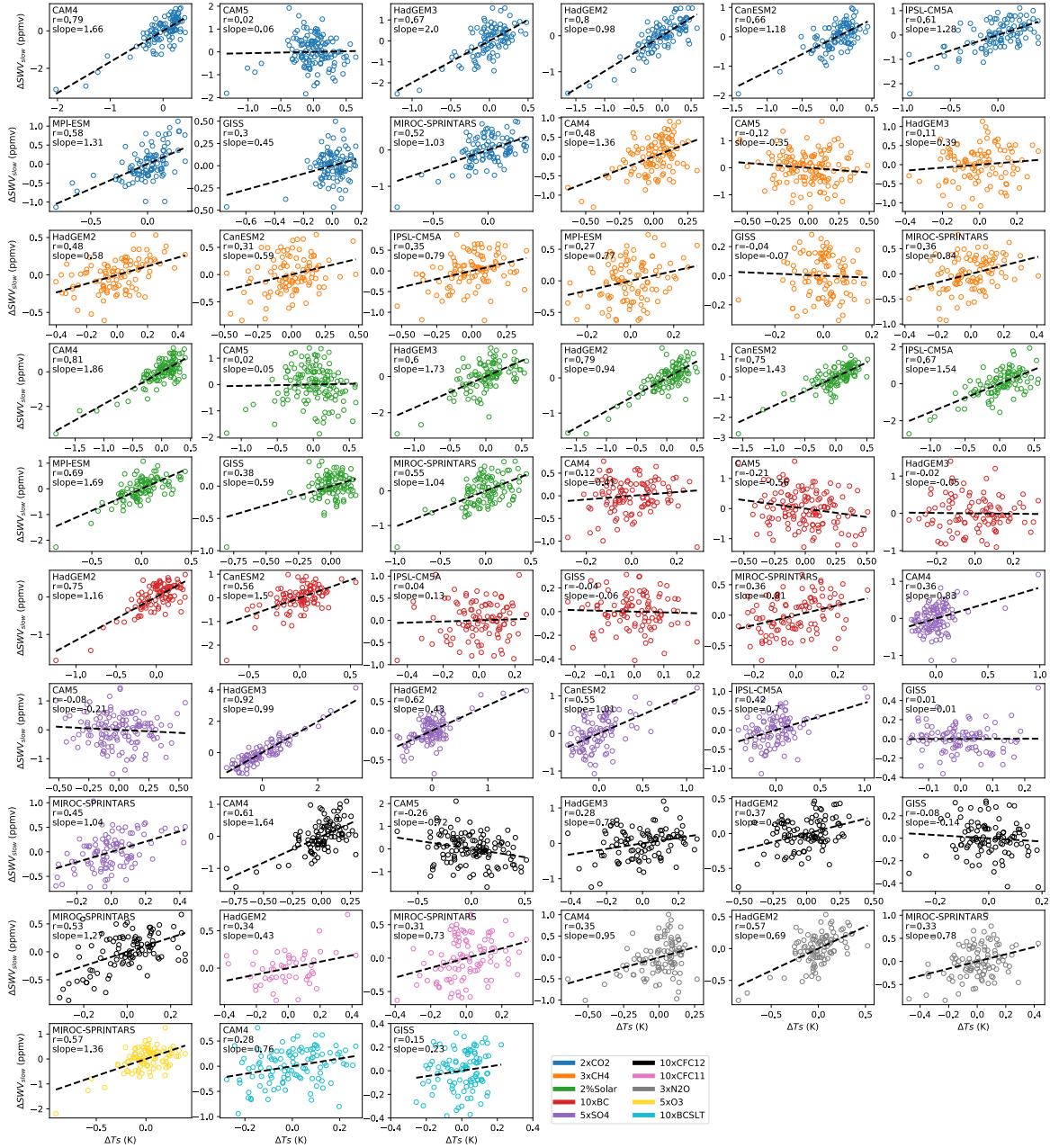


Figure S3. Same as Figure S1, but for ΔSWV_{slow} (ppmv) in the SH LMS.

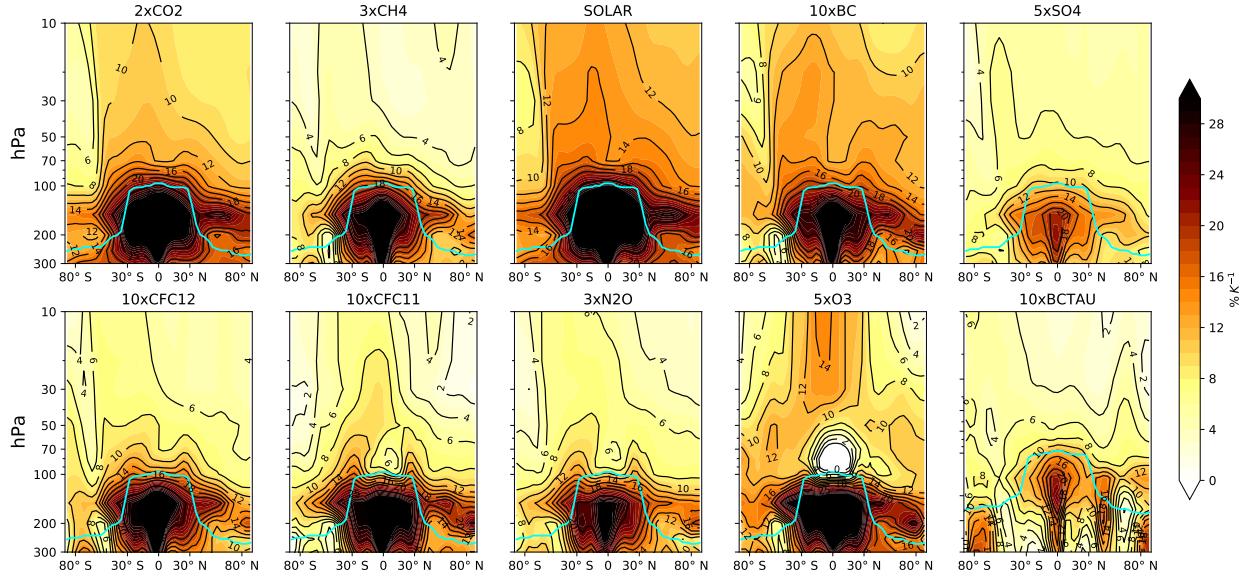


Figure S4. Ensemble average slope (%/K) for each individual perturbation from the regression between annual mean time series of $\Delta\text{SWV}_{\text{slow}}$ at each latitude grid point and pressure level and annual mean time series of global average ΔT s. We note that the 5xO3 shows weak $\Delta\text{SWV}_{\text{slow}}$ sensitivity to ΔT s in the TLS region. This corresponds to the weak equilibrium TLS $\Delta\text{SWV}_{\text{slow}}$, which consists a small part in the total equilibrium ΔSWV (less than 30%, Fig. 1d).