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Supplementary information

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# Multi-century cooling after net-zero greenhouse gas emissions

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**Supplementary Information for**

# Multi-century cooling after net-zero greenhouse gas emissions

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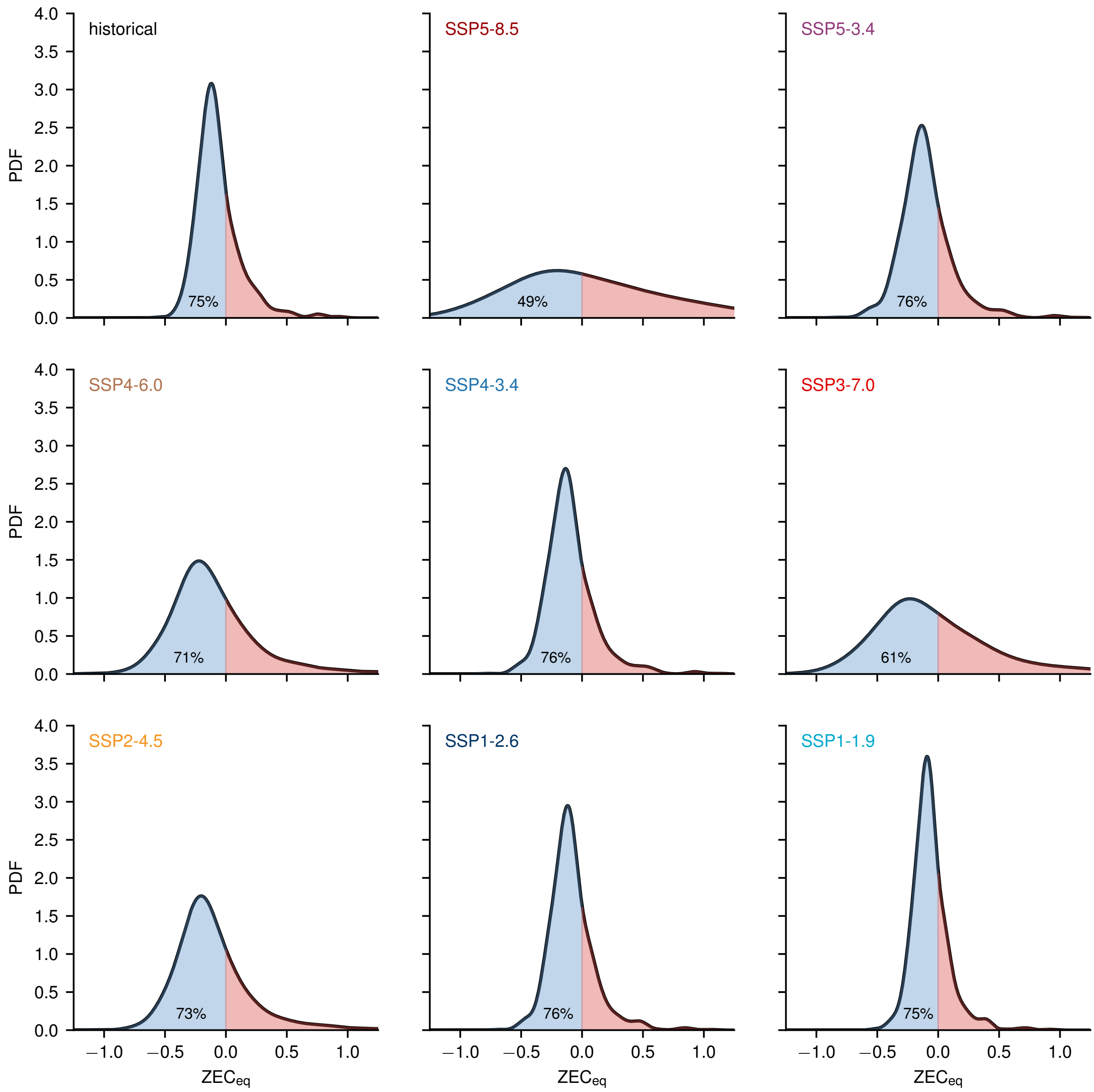
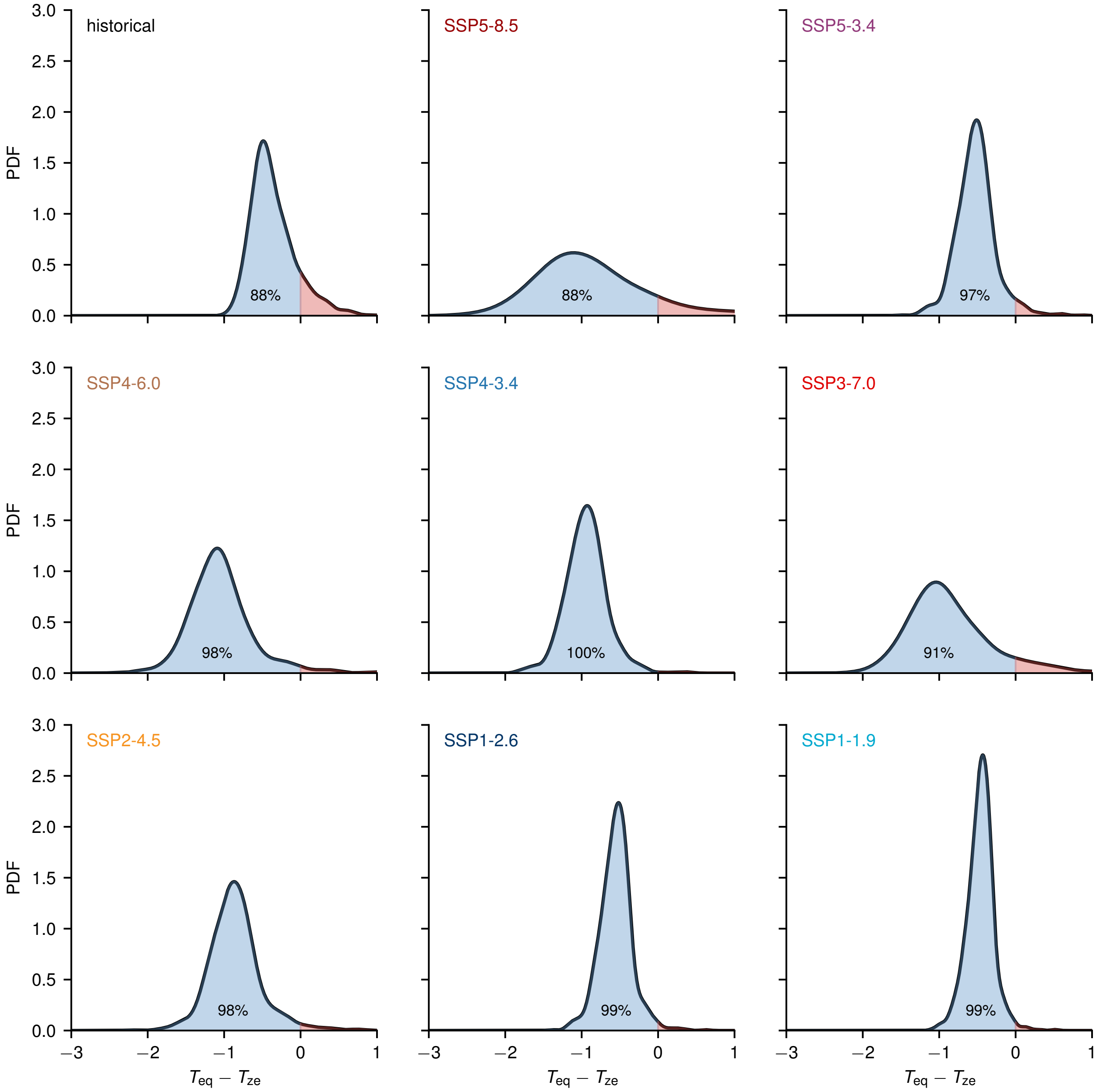
## Contents

This document contains Supplementary Figures 1–5 and Supplementary Tables 1–2.

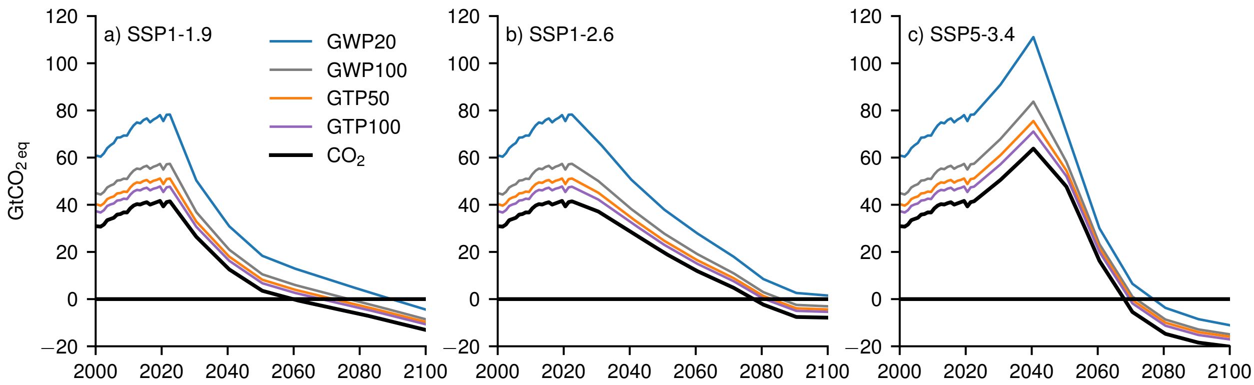
# Supplementary Figures



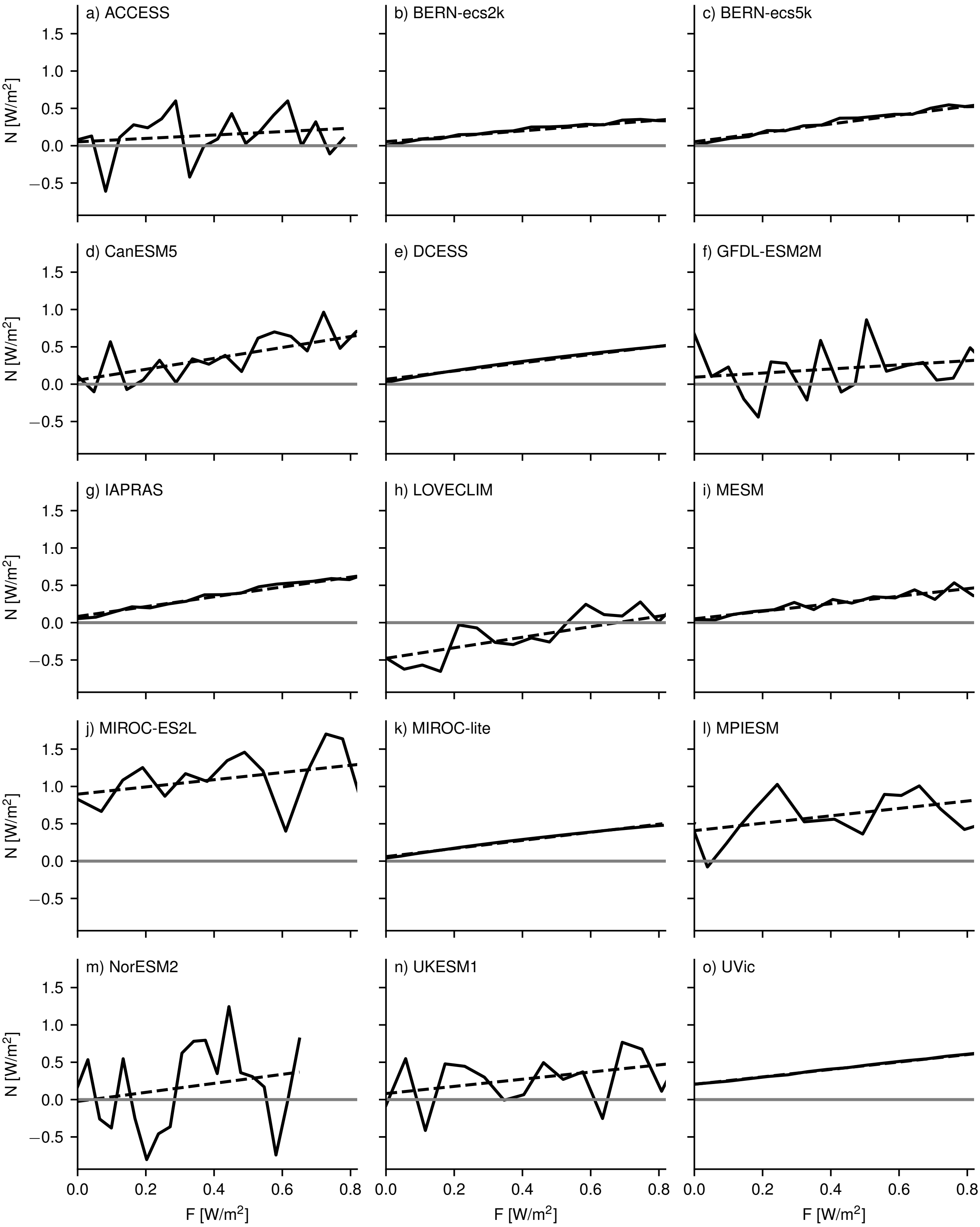

**Supplementary Fig. 1 | FaIR results for ZEC$_{eq}$ following cessation at 2100 in the $CO_2$-only SSPs.** The probability-density functions for the temperature change following cessation in year 2100 for the $CO_2$-only versions of the SSPs. Fraction of the ensemble that exhibits cooling is shaded in blue and labeled. Top left panel gives the result for cessation of historical $CO_2$ emissions in 2024. All scenarios are driven only by $CO_2$ changes and no other forcings. Compare to the all-forcing response in Supplementary Fig. 2.



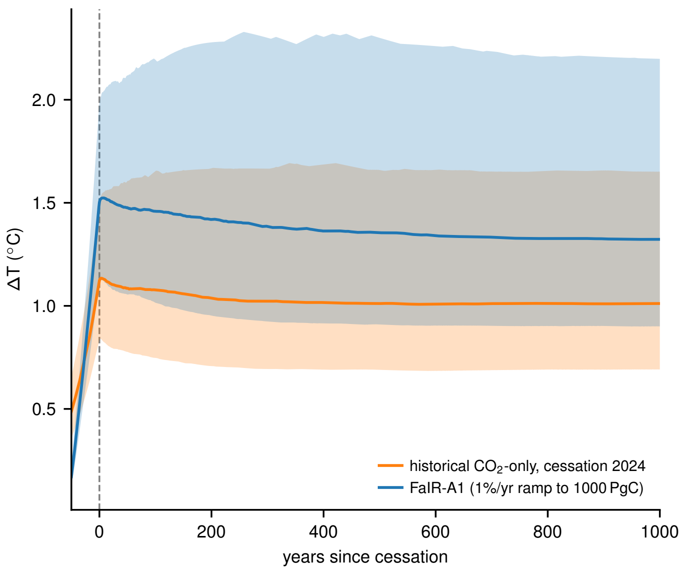

**Supplementary Fig. 2 | FaIR results for $T_{\mathbf{eq}} - T_{\mathbf{ze}}$ following cessation at 2100 in the SSPs.** The probability-density functions for the temperature change following cessation of all emissions in year 2100 for each respective SSP. Fraction of the ensemble that exhibits cooling is shaded in blue and labeled. Top left panel gives the result for cessation of historical emissions in 2024.




**Supplementary Fig. 3 | Mitigation SSP aggregate emissions under alternative metrics.** Shared Socioeconomic Pathway (SSP) mitigation emissions expressed in $CO_2$-equivalent units using GWP20 (blue), GWP100 (grey), GTP50 (orange), and GTP100 (purple), alongside true $CO_2$ emissions (black).




**Supplementary Fig. 4 | Initial energy imbalance in ZECMIP models.** The top-of-the-atmosphere energy imbalance $N$ versus the radiative forcing for ZECMIP models over the first 20 years of the 1%/yr $CO_2$ experiments. Linear regression (dotted) is performed to estimate the pre-industrial $N$, which may be non-zero due to energy conservation error or insufficient spin-up time.




**Supplementary Fig. 5 | Comparing ZEC in FaIR under ZECMIP-A1 protocol versus the historical $CO_2$-only.** Solid lines show the ensemble median, shaded bands the 5–95% range across the 841 FaIR configurations, with both experiments aligned at cessation. The A1 protocol is a 1%/yr $CO_2$ concentration ramp from preindustrial baseline, with cessation at the per-config year where diagnosed cumulative emissions first reach 1000 GtC. The historical experiment ceases $CO_2$ emissions in 2024.

# Supplementary Tables

**Supplementary Table 1 | Biogeochemical feedbacks omitted from the climate model.** AR6 biogeochemical climate feedback parameters (panel 5.29c) that are *not* included in FaIR v1.4.1. Central and 5–95% values read from AR6 WGI Fig. 5.29(c) and supporting text/tables. Ranges are combined by treating the uncertainty ranges as Gaussian, and correlations among feedbacks are not accounted for. Units: $\mathrm{W\,m^{-2}\,{}^\circ C^{-1}}$.

| Feedback (missing in FaIR) | Central estimate | 5–95% range | Reason missing |
| --- | --- | --- | --- |
| Fire $CO_2$ response to climate | +0.04 | N/A | No prognostic fire module; carbon-cycle tuning uses idealized C4MIP 1pct$CO_2$ (no fire). |
| Permafrost $CO_2$ response to climate | +0.09 | [+0.02, +0.20] | No permafrost module; not present in carbon-cycle training. |
| Permafrost $CH_4$ response to climate | +0.01 | [+0.003, +0.04] | No permafrost module. |
| Wetlands $CH_4$ response to climate | +0.03 | [+0.014, +0.046] | Natural $CH_4$ sources are held fixed. |
| $CH_4$-lifetime response to climate | −0.03 | [−0.12, +0.06] | Applied only to anthropogenic $CH_4$, thus not accounted for under zero emissions. |
| Land $N_2O$ response to climate | +0.02 | [+0.004, +0.04] | Natural $N_2O$ sources are held fixed. |
| Ocean $N_2O$ response to climate | −0.008 | [−0.011, −0.005] | Natural $N_2O$ sources are held fixed. |
| Lightning response to climate ($NO_x$) | −0.01 | [−0.04, +0.02] | Lightning is not represented. |
| BVOC response to climate | −0.05 | [−0.22, +0.12] | Natural BVOC sources are not prognosed. |
| Dust response to climate | −0.004 | [−0.02, +0.01] | Dust not represented. |
| Sea-salt response to climate | −0.05 | [−0.13, +0.03] | Sea-salt not represented. |
| DMS response to climate | +0.005 | [0.00, +0.01] | DMS not represented. |
| **Net** | +0.04 | [−0.19, +0.27] | |

**Supplementary Table 2 | Greenhouse gases with a positive residual forcing after offsetting.** Anthropogenic well-mixed greenhouse gases for which GWP100-neutral offsetting yields a *positive* residual net effective radiative forcing (ERF) at 100 yr. The sign of the residual forcing follows from Eq. 17 and requires that the species' persistence (defined by Eq. 20) satisfies $P_X(100) > P_{CO2} = 0.78$. ERF values are for 2019 relative to 1750 and are taken from IPCC AR6 WG1 Annex III [1, 2]. Entries reported as `N/A` indicate that a per-species ERF is not provided in the Annex III breakdown (typically because the contribution is too small to robustly estimate).

| Formula | Lifetime (yr) | $P_X(100)$ | ERF (W $m^{-2}$) |
|---|---|---|---|
| $SF_6$ | 3200 | 0.98 | 0.0056 |
| $CF_4$ | 50000 | 1.00 | 0.0051 |
| $C_2F_6$ | 10000 | 1.00 | 0.0013 |
| $NF_3$ | 569 | 0.91 | $4.2 \times 10^{-4}$ |
| $C_3F_8$ | 2600 | 0.98 | $1.8 \times 10^{-4}$ |
| n-$C_6F_{14}$ | 3100 | 0.98 | $9.9 \times 10^{-5}$ |
| n-$C_4F_{10}$ | 2600 | 0.98 | $7 \times 10^{-5}$ |
| n-$C_5F_{12}$ | 4100 | 0.99 | $5.7 \times 10^{-5}$ |
| $CClF_3$ | 640 | 0.92 | N/A |
| $CClF_2CF_3$ | 540 | 0.91 | N/A |
| $CHF_3$ | 228 | 0.80 | N/A |
| $CF_3CH_2CF_3$ | 213 | 0.78 | N/A |
| $N(C_2F_5)_3$ | 1000 | 0.95 | N/A |
| $N(CF_2CF_2CF_3)_3$ | 1000 | 0.95 | N/A |
| $N(CF_2CF_2CF_2CF_3)_3$ | 1000 | 0.95 | N/A |
| $N(CF_2CF_2CF_2CF_2CF_3)_3$ | 1000 | 0.95 | N/A |
| $SF_5CF_3$ | 800 | 0.94 | N/A |
| cyc (-$CF_2CF_2CF_2CF_2$-) | 3200 | 0.98 | N/A |
| n-$C_7F_{16}$ | 3000 | 0.98 | N/A |
| n-$C_8F_{18}$ | 3000 | 0.98 | N/A |
| $C_{10}F_{18}$ | 2000 | 0.98 | N/A |
| Z-$C_{10}F_{18}$ | 2000 | 0.98 | N/A |
| E-$C_{10}F_{18}$ | 2000 | 0.98 | N/A |
| $CF_3OCFCF_3CF_2OCF_2OCF_3$ | 800 | 0.94 | N/A |
| c-$C_4F_8O$ | 3000 | 0.98 | N/A |
| Total | | | 0.013 |

## References

[1] Dentener, F. J., Hall, B. & Smith, C. Annex III: Tables of Historical and Projected Well-mixed Greenhouse Gas Mixing Ratios and Effective Radiative Forcing of All Climate Forcers. In *Climate Change 2021: The Physical Science Basis* 2139–2152 (Cambridge University Press, Cambridge, UK and New York, NY, USA, 2021).

[2] IPCC. Scenarios and modelling methods. In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Guivarch, C. *et al.*) 1841–1908 (Cambridge University Press, Cambridge, UK and New York, NY, USA, 2022). DOI: 10.1017/9781009157926.022.