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The importance of an informed choice of CO_2-equivalence metrics for contrail avoidance

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Illustrative case studies of contrail avoidance

This section uses illustrative case studies to clarify Figure 4 and explain the behaviour of CO_2-equivalence metrics for different magnitudes of $EF_{contrail}$. The median flight of Section 3 (2450 km, 53 tons of CO_2) is again considered, and we again assume that it is possible to reroute the flight to avoid forming the persistent contrail with a 1% increase in the CO_2 emissions of the original flight.

Figure S1 illustrates the change in climate impact caused by such a rerouting for two different contrails. In both cases, the climate impact is quantified by combining AGWP, AGTP, or ATR with time horizons ranging from 1 to 100 years. Rerouting is assumed to have been successful with persistent contrail formation being completely avoided, although it should be noted that this assumption is overly optimistic and cannot be currently guaranteed in any realistic setting. The change in climate impact is quantified as the relative difference between the value of the metric for the rerouted flight and that of the original, contrail-forming flight. A negative relative difference indicates that rerouting provides a net climate benefit for the considered metric: the rerouted flight exerts a weaker radiative forcing (for AGWP) or a smaller temperature change (for AGTP and ATR) than the original flight. Conversely, a positive relative difference indicates that rerouting has made the net climate impact of the flight worse.

The first case, shown in Figure S1(a), corresponds to the formation of a high-energy contrail, with an energy input to the climate system of 2.8×10^{11} J km^{-1} applied to the 2450 km of the flight. That is ten times the energy of the median contrail energy forcing in the dataset, and only 10% of North Atlantic flights input more average contrail energy per kilometre. The decision making in this situation is easy: rerouting would yield a climate benefit, which would persist even with much larger additional CO_2 emissions. With a 20-year time horizon, rerouting decreases the climate impact by 95% if AGWP and ATR are used, and by about 70% if AGTP is used. With a 100-year time horizon, the reduction of climate impact exceeds 50% for all metrics.

The second case, shown in Figure S1(b), corresponds to the formation of a low-energy contrail with energy of 2.9×10^{10} J km^{-1}, which is the energy of the median contrail energy forcing in the dataset. In this case again, rerouting to avoid the contrail leads to a climate benefit. But the quantification of that climate benefit strongly depends on the choice of CO_2-equivalence metric. According to AGTP, the climate benefit associated with rerouting is less than 20% for time horizons longer than 20 years, falling to 10% at 100 years. AGWP and ATR are more permissive and indicate a reduction of about 60% of the climate impact at 20 years, decreasing to 30% at 100 years.

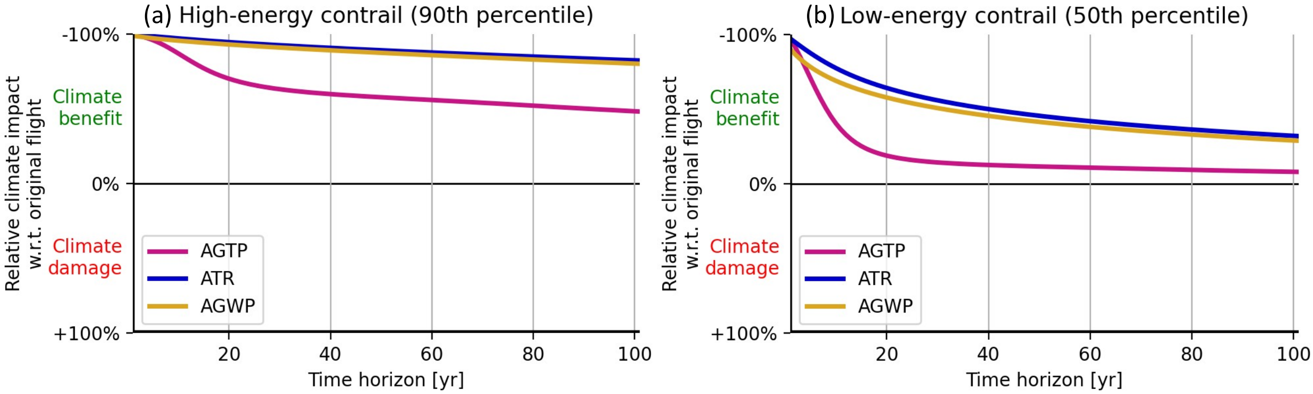


Figure S1: Change in climate impact due to rerouting a flight to avoid contrail formation as a function of time horizon, in years, according to different CO_2-equivalence metrics. The original flight emits 53 tonnes of CO_2 and is assumed to be successfully rerouted to avoid the formation of a persistent contrail of energy **(a)** 2.8×10^{11} J km^{-1} or **(b)** 2.9×10^{10} J km^{-1}, assuming a contrail efficacy of 0.35. Contrail energy forcing is applied over the whole 2450-km flight. The climate outcome of rerouting is shown as the relative difference between the rerouted flight climate impact and the original flight one for three metric definitions, AGTP (purple), ATR (blue), and AGWP (orange).

In addition to these two cases of contrail avoidance, it is informative to consider a different situation. As stated above, 20% of the persistent contrails formed in the North Atlantic have a negative energy forcing, thereby cooling the climate. Contrail radiative forcing uncertainties are such that we cannot yet confidently predict that a particular ISSR would lead to the formation of strongly warming or cooling persistent contrails. This is illustrated in Table 2 of Teoh et al. (2020), whereby the 2.5 to 97.5% confidence interval of the energy of a “big hit” contrail of energy 4.33 10^{15} J spans a range from -1×10^{13} to 17.1×10^{15} J, so includes a low probability that the contrail is in fact cooling. Figure S2 illustrates the case where the original flight would have formed a contrail with an energy of -6.0×10^{9} J km^{-1}, which is about a fifth of the median contrail in the dataset, with a negative sign. 10% of contrails from transatlantic flights cool more than this value. As before, rerouting the aircraft would avoid the formation of that contrail. As expected, rerouting that flight damages the climate, for all metrics and time horizon considered. The increase in climate impact exceeds 35% and 55% for time horizons shorter than 20 years when using AGWP and ATR, respectively, with an increase of about 10% at a time horizon of 100 years. Climate damage is less according to AGTP, at 6% at 20 years and about 3% at 100 years.

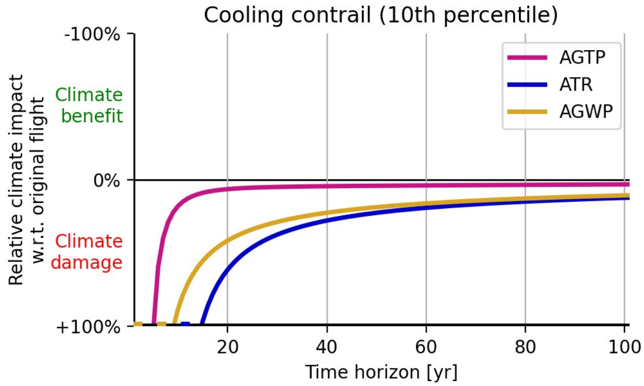


Figure S2: As for Figure S1, but for a change in climate impact due to rerouting a flight that would have formed a cooling contrail of energy -6.0×10^{9} J km^{-1}.

Those idealised cases suggest that the three CO_2-equivalence metrics give similar information for the decision to reroute or not but lead to very different quantifications of the climate outcome. $AGTP_H$ generally leads to a smaller estimate of the climate benefit or damage than the time-integrated metrics $AGWP_H$ and ATR_H. Short time horizons yield to larger climate outcomes than long time horizons, with differences being especially large when contrail energy is low. There is a range of contrail EF where at least one CO_2-equivalence metric leads to a different rerouting decision than the others. For our typical flight and our nine CO_2-equivalence metrics, that range spans the 24th to the 31st percentiles, i.e. 7% of the contrail-forming flights. This range represents very low-energy contrails, with EF per flown kilometre from 1.7×10^{8} to 3.1×10^{9} J km^{-1}. This second value is about a tenth of the median contrail energy forcing in the dataset.

Values corresponding to Figures 3 and 5 of the main text.

Table S1: Summary of the OSCAR calculation of AGWP, in mW m^{-2} yr, AGTP, in µK, and ATR, in <µK>, due to CO_2 emissions and warming and cooling contrail formation for the flights that crossed the North Atlantic sector in 2019 (Teoh et al., 2022). Calculations are given for three time horizons: 20, 50, and 100 years. Percentages in brackets are relative to the first column "All flights". For ATR, the unit is denoted <µK> to distinguish an average over the time horizon from an endpoint temperature change.

RF or warming caused by specific climate forcer	All climate forcers	CO_2 emissions	Warming contrails ($EF_{contrail}$ > 0 J km^{-1})	Cooling contrails ($EF_{contrail}$ < 0 J km^{-1})
AGWP100	3.94 mW m^{-2} yr	2.32 mW m^{-2} yr (59%)	1.70 mW m^{-2} yr (43%)	−0.07 mW m^{-2} yr (−2%)
AGWP50	2.91 mW m^{-2} yr	1.32 mW m^{-2} yr (45%)	1.66 mW m^{-2} yr (57%)	−0.07 mW m^{-2} yr (−2%)
AGWP20	2.22 mW m^{-2} yr	0.67 mW m^{-2} yr (30%)	1.62 mW m^{-2} yr (73%)	−0.07 mW m^{-2} yr (−3%)
AGTP100	14.1 µK	12.1 µK (86%)	2.06 µK (15%)	−0.09 µK (−1%)
AGTP50	13.7 µK	11.0 µK (80%)	2.73 µK (20%)	−0.12 µK (−1%)
AGTP20	17.2 µK	12.2 µK (71%)	5.17 µK (30%)	−0.22 µK (−1%)
ATR100	20.9 <µK>	11.5 <µK> (55%)	9.75 <µK> (47%)	−0.42 <µK> (−2%)
ATR50	28.0 <µK>	11.6 <µK> (41%)	17.2 <µK> (61%)	−0.74 <µK> (−3%)
ATR20	48.2 <µK>	12.0 <µK> (25%)	37.8 <µK> (78%)	−1.63 <µK> (−3%)

Table S2: As Table S1, but now separating flights into categories depending on their overall climate impact. The number of flights for the last two categories depends on the metric.

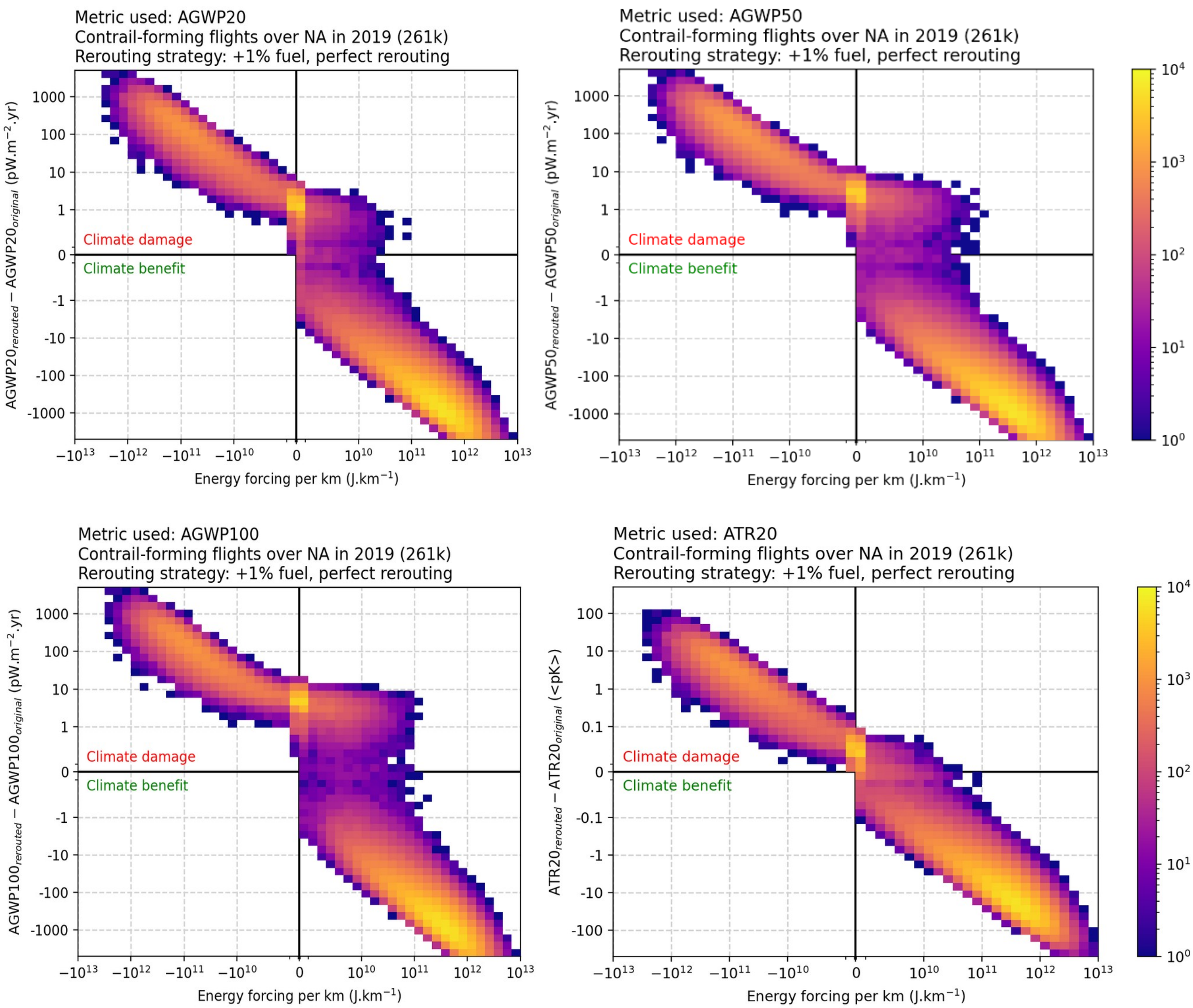
Flight subset	All flights	Contrail-forming flights	Flights forming warming contrails	Flights forming cooling contrails that cool less than CO_2 warming	Flights forming cooling contrails that cool more than CO_2 warming
Number of flights	477,923	260,854 (55%)	208,965 (44%)		
AGWP100	3.94 mW m^{-2} yr	2.99 mW m^{-2} yr (76%)	2.78 mW m^{-2} yr (71%)	0.21 mW m^{-2} yr (5%) 47,306 flights	−0.015 mW m^{-2} yr 4,583 flights
AGWP50	2.91 mW m^{-2} yr	2.37 mW m^{-2} yr (81%)	2.28 mW m^{-2} yr (78%)	0.11 mW m^{-2} yr (4%) 43,417 flights	−0.025 mW m^{-2} yr 8,472 flights
AGWP20	2.22 mW m^{-2} yr	1.94 mW m^{-2} yr (87%)	1.93 mW m^{-2} yr (87%)	0.05 mW m^{-2} yr (2%) 37,717 flights	−0.038 mW m^{-2} yr 14,172 flights
AGTP100	14.1 μK	9.00 μK (64%)	7.70 μK (55%)	1.30 μK (9%) 51,649 flights	−0.001 μK 240 flights
AGTP50	13.7 μK	9.03 μK (66%)	7.88 μK (58%)	1.15 μK (8%) 51,272 flights	−0.003 μK 617 flights
AGTP20	17.2 μK	12.1 μK (70%)	10.9 μK (63%)	1.20 μK (7%) 49,919 flights	−0.020 μK 1,970 flights
ATR100	20.9 <μK>	16.0 <μK> (77%)	15.1 <μK> (72%)	1.00 <μK> (5%) 46,352 flights	−0.10<μK> 5,537 flights
ATR50	28.0 <μK>	23.2 <μK> (83%)	22.6 <μK> (81%)	0.89 <μK> (3%) 42,062 flights	−0.30<μK> 9,827 flights
ATR20	48.2 <μK>	43.2 <μK> (90%)	43.4 <μK> (90%)	0.75 <μK> (2%) 35,210 flights	−1.00<μK> 16,679 flights

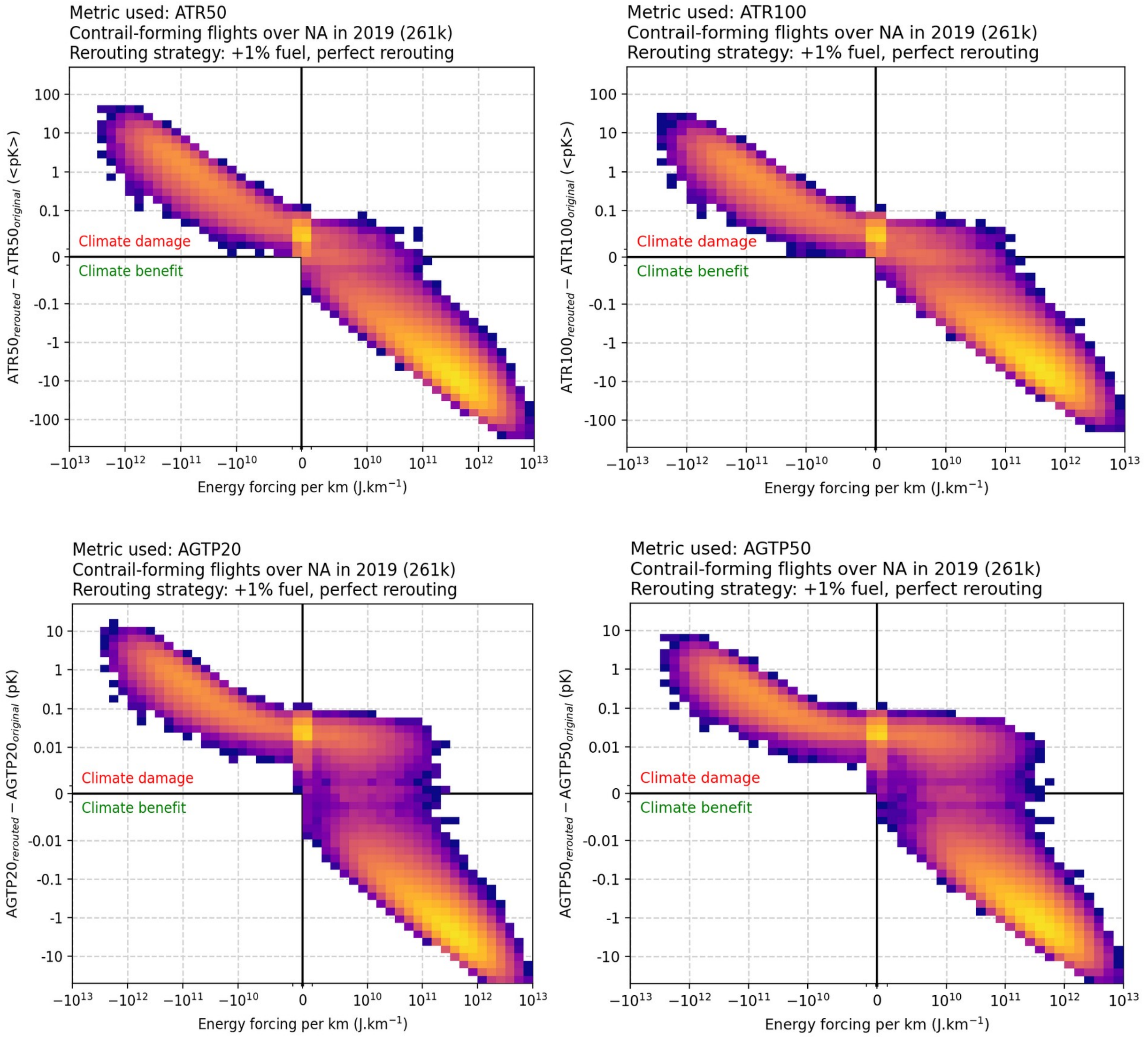
Table S3: Number of flights flown over the North Atlantic in 2019, out of a total of 260,854 contrail-forming flights, for different categories of climate outcomes of rerouting, depending on the CO_2-equivalence metric (given as a combination of metric definition and time horizon) and the additional CO_2 emitted to reroute. Rerouting is assumed to be successful, so the rerouted flight does not form a contrail and a contrail would have formed, as predicted, on the original route. Climate benefit happens when the CO_2-equivalence metric is lower for the rerouted flight than for original flight. Percentages in brackets are calculated with respect to the 1% additional CO_2 scenario in each case. Column 5 gives the absolute climate benefit of all reroutings, with a unit that depends on the CO_2-equivalence metric. For ATR, the unit is denoted <μK> to distinguish an average over the time horizon from an endpoint temperature change. The potential "lower risk" rerouting category in the second to last column refers to flights with an energy forcing larger than 10^{11} J km^{-1} and whose climate benefit from contrail avoidance is 100 times larger than the climate damage from emitting 1% more CO_2. The absolute climate benefit from rerouting these flights is indicated in the last column.

CO_2-equivalence metric used	Additional CO_2 emitted	Number of reroutings that lead to climate damage	Number of reroutings that lead to climate benefit	Climate benefit (unit is metric-dependent)	Potential "lower risk" rerouting	Climate benefit of potential "lower risk" rerouting
AGWP100	0%	51,889 (−25%)	208,965 (+9%)	1.62 mW m^{-2} yr	143,369	1.66 mW m^{-2} yr
	+1%	69,410	191,444	1.61 mW m^{-2} yr	89,052	1.49 mW m^{-2} yr
	+2%	74,100 (+7%)	186,754 (−2%)	1.60 mW m^{-2} yr	55,592	1.24 mW m^{-2} yr
	+5%	83,521 (+20%)	177,333 (−7%)	1.56 mW m^{-2} yr	19,166	0.69 mW m^{-2} yr
AGWP50	0%	51,889 (−22%)	208,965 (+8%)	1.59 mW m^{-2} yr	143,369	1.62 mW m^{-2} yr
	+1%	66,606	194,248	1.58 mW m^{-2} yr	111,429	1.56 mW m^{-2} yr
	+2%	70,309 (+6%)	190,545 (−2%)	1.57 mW m^{-2} yr	81,737	1.42 mW m^{-2} yr
	+5%	77,375 (+16%)	183,479 (−6%)	1.55 mW m^{-2} yr	38,620	1.01 mW m^{-2} yr
AGWP20	0%	51,889 (−19%)	208,965 (+6%)	1.55 mW m^{-2} yr	143,369	1.58 mW m^{-2} yr
	+1%	63,944	196,910	1.54 mW m^{-2} yr	129,648	1.56 mW m^{-2} yr
	+2%	66,798 (+4%)	194,056 (−1%)	1.54 mW m^{-2} yr	109,979	1.51 mW m^{-2} yr
	+5%	72,045 (+13%)	188,809 (−4%)	1.53 mW m^{-2} yr	68,851	1.30 mW m^{-2} yr
AGTP100	0%	51,889 (−36%)	208,965 (+17%)	1.97 μK	143,369	2.01 μK

	+1%	81,628	179,226	1.90 μK	23,843	0.95 μK
	+2%	91,614 (+12%)	169,240 (−6%)	1.83 μK	7,314	0.43 μK
	+5%	111,388 (+36%)	149,466 (−17%)	1.62 μK	899	0.07 μK
AGTP50	0%	51,889 (−33%)	208,965 (+14%)	2.61 μK	143,369	2.67 μK
	+1%	77,528	183,326	2.55 μK	37,915	1.65 μK
	+2%	85,797 (+11%)	175,057 (−5%)	2.49 μK	14,610	0.92 μK
	+5%	102,181 (+32%)	158,673 (−13%)	2.29 μK	2,259	0.22μK
AGTP20	0%	51,889 (−29%)	208,965 (+11%)	4.95 μK	143,369	5.05 μK
	+1%	73,026	187,828	4.88 μK	62,572	3.98 μK
	+2%	79,169 (+8%)	181,685 (−3%)	4.81 μK	31,687	2.83 μK
	+5%	91,667 (+26%)	169,187 (−10%)	4.60 μK	7,268	1.06 μK
ATR100	0%	51,889 (−24%)	208,965 (+9%)	9.33 <μK>	143,369	9.52 <μK>
	+1%	68,602	192,252	9.27 <μK>	95,378	8.77 <μK>
	+2%	73,043 (+6%)	187,811 (−2%)	9.20 <μK>	62,442	7.50 <μK>
	+5%	81,696 (+19%)	179,158 (−7%)	9.00 <μK>	23,624	4.49 <μK>
ATR50	0%	51,889 (−21%)	208,965 (+7%)	16.4 <μK>	143,369	16.7 <μK>
	+1%	65,803	195,051	16.3 <μK>	117,053	16.3 <μK>
	+2%	69,355 (+5%)	191,499 (−2%)	16.3 <μK>	89,518	15.1 <μK>
	+5%	75,896 (+15%)	184,958 (−5%)	16.1 <μK>	45,776	11.4 <μK>
ATR20	0%	51,889 (−18%)	208,965 (+6%)	36.2 <μK>	143,369	36.9 <μK>
	+1%	62,976	197,878	36.1 <μK>	134,103	36.7 <μK>
	+2%	65,554 (+4%)	195,300 (−1%)	36.1 <μK>	119,000	36.0 <μK>
	+5%	70,285 (+12%)	190,569 (−4%)	35.8 <μK>	81,948	32.4 <μK>

Figure S3: Figure 4 shows the climate outcome of rerouting in terms of the AGTP100. The Figures below show the climate outcome expressed in terms of the other eight CO_2-equivalence metrics: AGWP20, AGWP50, AGWP100, ATR20, ATR50, ATR100, AGTP20, and AGTP50.




Metric used: ATR50
Contrail-forming flights over NA in 2019 (261k)
Rerouting strategy: +1% fuel, perfect rerouting
Climate damage
Climate benefit
ATR50_rerouted − ATR50_original (<pK>)
Energy forcing per km (J.km⁻¹)
Metric used: ATR100
Contrail-forming flights over NA in 2019 (261k)
Rerouting strategy: +1% fuel, perfect rerouting
Climate damage
Climate benefit
ATR100_rerouted − ATR100_original (<pK>)
Energy forcing per km (J.km⁻¹)
Metric used: AGTP20
Contrail-forming flights over NA in 2019 (261k)
Rerouting strategy: +1% fuel, perfect rerouting
Climate damage
Climate benefit
AGTP20_rerouted − AGTP20_original (pK)
Energy forcing per km (J.km⁻¹)
Metric used: AGTP50
Contrail-forming flights over NA in 2019 (261k)
Rerouting strategy: +1% fuel, perfect rerouting
Climate damage
Climate benefit
AGTP50_rerouted − AGTP50_original (pK)
Energy forcing per km (J.km⁻¹)