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Estimating the climate impact of linear contrails using the UK Met Office climate model

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[1] The HadGEM2 global climate model is employed to investigate some of the linear contrail effects on climate. Our study parameterizes linear contrails as a thin layer of aerosol. We find that at 100 times the air traffic of year 2000, linear contrails would change the equilibrium global-mean temperature by +0.13 K, corresponding to a climate sensitivity of 0.3 K/(Wm^{-2}) and a climate efficacy of 31% (significantly smaller than the only previously published estimate of 59%). Our model suggests that contrails cause a slight warming of the surface and, as noted by most global warming modelling studies, land areas are affected more than the oceans. Also, unlike the contrail coverage and radiative forcing, the contrail temperature change response is not geographically correlated with air traffic patterns. In terms of the contrail impact on precipitation, the main feature is the northern shift of the Inter-Tropical Convergence Zone. Finally, our model strongly indicates that the contrail impact on both the diurnal temperature range and regional climate is significantly smaller than some earlier studies suggested. **Citation:** Rap, A., P. M. Forster, J. M. Haywood, A. Jones, and O. Boucher (2010), Estimating the climate impact of linear contrails using the UK Met Office climate model, *Geophys. Res. Lett.*, *37*, L20703, doi:10.1029/2010GL045161.

1. Introduction

[2] The largest uncertainty in the study of aviation impact on climate, and potentially the most significant, remains the one associated with contrails (both linear contrails and contrail-induced cirrus) [e.g., *Boucher*, 1999; *Lee et al.*, 2009; *Burkhardt et al.*, 2010]. The subject has received a lot of attention in the media especially soon after the publication of the papers by *Travis et al.* [2002, 2004], where the three-day grounding period of commercial aircraft over the United States of America (USA) after the terrorist attacks on 11 September 2001 was investigated. They concluded that the diurnal temperature range (DTR) averaged across the USA was significantly increased (by at least 1.1 K) during that period due to the absence of contrails. Since then, several studies have argued against this hypothesis. *Dietmüller et al.* [2008] used the ECHAM4 GCM and analysis of long term DTR trends to show that there is no significant contrail impact on the DTR and, therefore, that the hypothesis lacks sufficient statistical backing. *Hong et al.* [2008] have shown that the average DTR recorded over the USA during 11–14 September 2001 was within the range of natural variability observed from 1971 to 2001 and the DTR increase during the grounding period cannot be attributed to the lack of contrails, but more probably to anomalies in low cloudiness.

[3] Another interesting debate relates to the relative role of contrail-driven surface temperature change over the continental USA. *Minnis et al.* [2004] hypothesised that contrails and aviation cirrus could explain all the observed surface temperature increase trend of 0.27 K/decade over the continental USA between 1971 and 1995. *Shine* [2005], *Ponater et al.* [2005], and *Dietmüller et al.* [2008] argued against this hypothesis, concluding that *Minnis et al.* [2004] overestimated the regional surface temperature response to contrails.

[4] These debates have been difficult to resolve as the climate impact of contrails still remains poorly understood and quantified. It is therefore very important to improve the scientific understanding associated with contrails and their climatic impact, especially in the current situation when the steady increase in air traffic over the last few decades (which led to a significant increase in global contrail coverage [e.g., *Rädel and Shine*, 2008; *Rap et al.*, 2010]) has to be reconciled with the stringent need for action to tackle climate change.

[5] To date, the only equilibrium climate change simulation with a global climate model that includes contrails is *Ponater et al.*'s [2005] study, which used the ECHAM4 climate model to estimate a contrail climate sensitivity of 0.43 K/(Wm^{-2}) and a contrail climate efficacy of 59% (climate efficacy is the climate sensitivity normalized to that of CO_2). The aim of the present study is to employ *Rap et al.*'s [2010] linear contrail parameterisation that was developed for the Met Office climate model in order to produce another independent estimate for contrail climate sensitivity and efficacy and to investigate some of the climatic impact responses due to linear contrails such as DTR changes.

2. Model and Simulation Setup

[6] The model used was a developmental version of the HadGEM2 climate model [*Collins et al.*, 2008]. The atmospheric component, with a resolution of 1.25° latitude by 1.875° longitude and 38 vertical levels, has been extended by a linear contrail parameterisation, as described by *Rap et al.* [2010]. This is coupled to a 50m thermodynamic mixed-layer ocean and sea ice model ('slab' model), as described by *Johns et al.* [2006]. This model has previously been used to model the climate response to the radiative forcing by sulphate, black carbon, and biomass burning aerosols as well as that due to CO_2 [*Jones et al.*, 2007].

[7] Based on contrail formation thermodynamics [*Schumann*, 1996] and ambient meteorological conditions,

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Table 1. Annual Global Mean Contrail RF for Different Global Mean Grid Box Equivalent Contrail Optical Depths

$\tau_{\text{gridbox\_contrail}}$	LW RF [mWm^{-2}]	SW RF [mWm^{-2}]	|LW/SW| RF ratio	Net RF [mWm^{-2}]
1.4×10^{-4}	6.3	−2.4	2.6	3.9
2.8×10^{-4}	11.5	−3.8	3.0	7.7
4.2×10^{-4}	17.1	−5.5	3.1	11.6
1.4×10^{-3}	57.2	−21.6	2.7	35.6
1.4×10^{-2}	497	−195	2.6	302
2.8×10^{-2}	714	−284	2.5	430

the linear contrail parameterisation from *Rap et al.* [2010] simulates at each time step (30 minutes) a contrail coverage, optical depth and radiative forcing. According to this parameterisation, for the air traffic of year 2002, the annual global mean contrail coverage is 0.11% and the annual global mean contrail top of atmosphere radiative forcing is 7.7 mWm^{-2}, if an annual global mean contrail optical depth of 0.2 is assumed.

[8] Three slab-ocean experiments have been set up: (i) a 50-year control run (CNTL), (ii) an enhanced contrail run (ECON, also 50 years), and (iii) a 30-year 2xCO$_2$ run (2xCO$_2$). As described by *Rap et al.* [2010], for technical reasons, in the linear contrail parameterisation developed for the Met Office climate model, the contrail was introduced as a new aerosol species and both the contrail coverage b_{contrail}, and the contrail optical depth τ_{contrail}, were controlled in the model by altering a grid box equivalent contrail optical depth, $\tau_{\text{gridbox\_contrail}} = b_{\text{contrail}} \times \tau_{\text{contrail}}$. The global means for these three quantities, corresponding to the air traffic of year 2002, are $b_{\text{contrail}} = 0.11\%$, $\tau_{\text{contrail}} = 0.2$, and $\tau_{\text{gridbox\_contrail}} = 2.8 \times 10^{-4}$. In the ECON experiment, in order to obtain a large enough radiative forcing that provides a response readily detectable above the natural variability simulated by the model, the grid box equivalent contrail optical depth was multiplied by a factor of 100, leading to a global mean of $\tau_{\text{gridbox\_contrail}} = 2.8 \times 10^{-2}$. As shown by *Rap et al.* [2010], we found a sufficiently linear RF behaviour for a global mean τ_{contrail} range of 0.003– 0.5 ($\tau_{\text{gridbox\_contrail}}$ range of 4.2×10^{-6}–7.1×10^{-4}), but this cannot necessarily be extrapolated for higher mean grid box equivalent contrail optical depths such as $\tau_{\text{gridbox\_contrail}} = 2.8 \times 10^{-2}$. In fact, as shown in Table 1, the RF behaviour is considerably less linear for the larger optical depths. This is mainly due to radiative forcing saturation in regions such as the USA, Asia and Europe, where annual mean grid box equivalent contrail optical depths reach values as large as $\tau_{\text{gridbox\_contrail}} = 2$. However, for the whole optical depth range investigated, we are in a reasonably linear regime in terms of LW versus SW RFs, i.e. the magnitude of the LW/SW ratio is relatively constant for all optical depths, varying only between 2.5 and 3.1. This suggests that the enhancement of contrails in the ECON experiment does not significantly change the high-level cloud regime and therefore does not affect the suitability of this parameterisation for the present study.

[9] The radiative forcing saturation for larger grid box equivalent contrail optical depths means that the annual global mean RF for the ECON experiment is only approximately 55 times higher than the original (430 mWm^{-2} compared to 7.7 mWm^{-2}) although the optical depth was multiplied by a factor of 100. Thus, the ECON experiment should be regarded as a 55xContrail simulation. The 2xCO$_2$

experiment was also included for estimation of the contrail efficacy and for a direct comparison of the contrail effects on climate with those of doubling CO$_2$.

3. Contrail Climate Sensitivity and Impact

[10] The three experiments reach an equilibrium state after the first 10 years of simulation. The last 40 (CNTL & ECON) or 20 (2xCO$_2$) years of simulation were averaged to obtain some representative values of equilibrium climate change simulations. Figures 1a and 1b show the equilibrium surface temperature response in the ECON and the 2xCO$_2$ simulations, respectively. The global mean changes in the two cases are 0.13 K and 3.64 K, respectively. One of the first things to note is the fact that the geographical pattern of the surface temperature response to contrails is significantly spread out
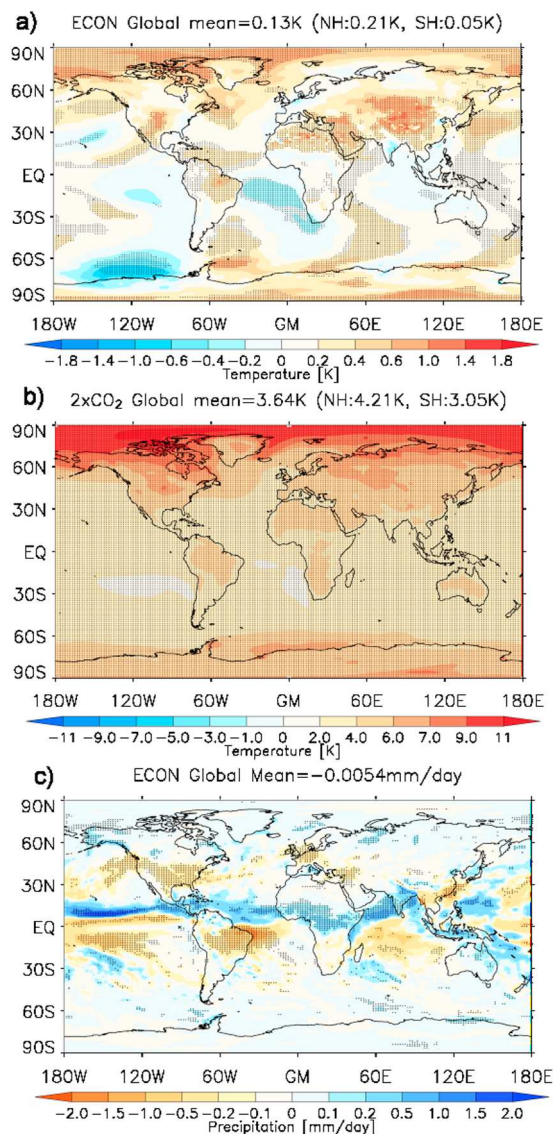
Figure 1. Equilibrium changes for surface temperature [K] from (a) the ECON and (b) the 2xCO$_2$ experiments, and (c) precipitation [mm/day] from the ECON experiment. The stippling indicates regions where changes are significant at the 5% level.

Table 2. Climate Sensitivity and Efficacy for Contrails and CO_2

Study	Climate Sensitivity [K/(Wm^{-2})]		Climate Efficacy [%]	
	Contrails	CO$_2$	Contrails	CO$_2$
ECHAM4				
Ponater et al. [2005]	0.43	0.73	59	100
(95% confidence int.)	(0.35,0.51)		(48,70)	
HadGEM2-AML				100
This study	0.3	0.98	31	
(95% confidence int.)	(0.16, 0.44)	(0.84,1.12)	(17, 45)	

compared to the contrail radiative forcing pattern presented by *Rap et al.* [2010]. Thus, while the geographical distributions of air traffic, contrail coverage, optical depth and radiative forcing are well correlated, there seems to be no geographic correlation between contrail forcing and contrail surface temperature response. This is consistent with the findings of *Ponater et al.* [2005], who used the ECHAM4 climate model, as well as previous knowledge on forcing-response relationships [e.g., *Forster et al.*, 2000]. Also, as in other global warming studies, we note that there is a significant general tendency of the land areas to warm more than the oceans.

[11] The slab-ocean model simulations also allow the estimation of the climate sensitivity parameter, λ [K/(Wm^{-2})], given by the following expression:

$$\lambda = \frac{\Delta T}{\Delta F}$$

where ΔT is the equilibrium global mean near-surface temperature change and ΔF is the global mean radiative forcing.

[12] For the ECON simulation, combining the contrail RF estimates ($\Delta F = 0.43$ Wm^{-2}) with the contrail surface temperature change ($\Delta T = 0.13$ K) results in a contrail climate sensitivity $\lambda_{contrails} = 0.3$ K/(Wm^{-2}). After accounting for auto-correlation as suggested by *Zwiers and von Storch* [1995], the 95% confidence interval for this contrail climate sensitivity value is [0.16,0.44] K/(Wm^{-2}). The corresponding CO_2 climate sensitivity, calculated using the 2xCO_2 simulation, is $\lambda_{CO2} = 0.98$ K/(Wm^{-2}), therefore giving a contrail climate efficacy of 31%, with the 95% confidence interval [17,45] %. *Andrews et al.* [2010] used the same developmental version of the HadGEM2 climate model and a lower CO_2 forcing of 1.39 Wm^{-2} (corresponding to a CO_2 concentration increased from 1860 to 2005 levels) and found a CO_2 climate sensitivity similar to the one calculated in a 2xCO_2 simulation (T. Andrews, personal communication, 2010).

[13] The only other estimate for the contrail climate sensitivity is the one of *Ponater et al.* [2005], where the value of $\lambda_{contrails}$ was 0.43 K/(Wm^{-2}) with the 95% confidence interval [0.35,0.51] K/(Wm^{-2}). Their corresponding CO_2 climate sensitivity, calculated from an experiment forced by a radiative forcing change of 1 Wm^{-2}, was $\lambda_{CO2} = 0.73$ K/(Wm^{-2}), giving a contrail climate efficacy of 59% with the 95% confidence interval [48,70] %. As shown in Table 2, both the contrail climate sensitivity and contrail efficacy estimated here are smaller than those estimated by *Ponater et al.* [2005] using ECHAM4.

[14] The impact on the precipitation equilibrium changes from the enhanced linear contrails experiment is illustrated in Figure 1c. In terms of annual global means, our model
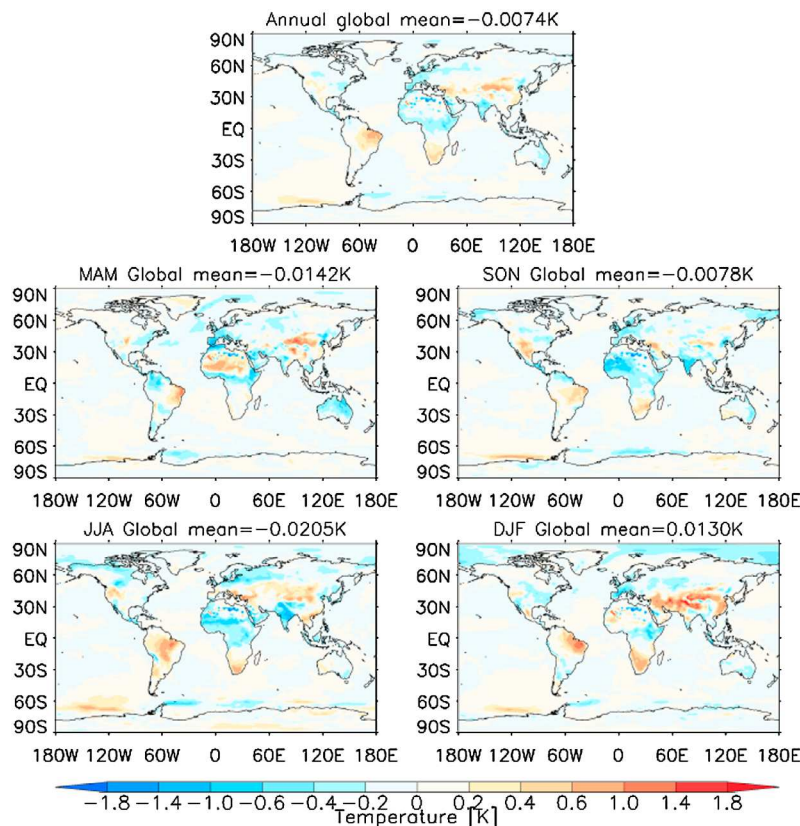
Figure 2. Annual and seasonal diurnal temperature range [K] equilibrium changes from the ECON experiment. Changes are significant at the 5% level at almost all points.
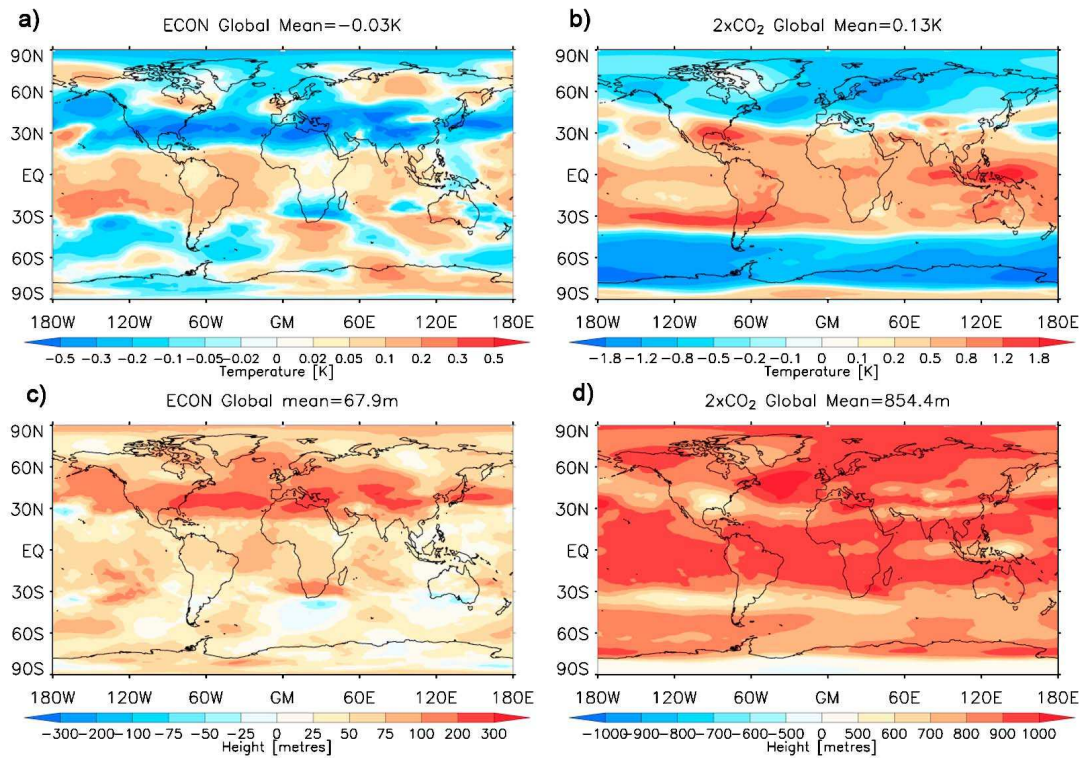
Figure 3. Tropopause (a, b) temperature [K] and (c, d) height [m] equilibrium changes from the ECON and the 2xCO2 experiments, respectively.

suggests that linear contrails cause a slight decrease of precipitation (with a global mean of −0.005 mm/day for the ECON simulation). In the $2xCO_2$ experiment we recorded an increase in the amount of precipitation (with a global mean of 0.154 mm/day). However, the most important effect on precipitation is probably the fact that the Inter-Tropical Convergence Zone (ITCZ) is moved northward. As explained by *Williams et al.* [2001] and *Jones et al.* [2007], this is mainly caused by the different temperature change of the two hemispheres, with the northern hemisphere warming relatively more than the southern hemisphere, i.e. 0.21 K compared with 0.05 K, see Figure 1a. This northward shift of the ITCZ causes precipitation to decrease in northeast Brazil and increase in the central African and Indian monsoon regions (which supports the slight cooling shown in Figure 1a for northeast India). All these regional features are consistent with findings from both *Roberts and Jones* [2004] and *Jones et al.* [2007] for other forcing mechanisms.

[15] Figure 2 shows the DTR equilibrium changes estimated in the ECON experiment, in both annual and seasonal means. The annual global mean DTR is reduced by 0.007 K, with the largest contribution (almost 3 times the annual average) coming from the northern hemisphere summer months. In one season, i.e., the northern hemisphere winter which also corresponds to the season with the smallest amounts of air traffic and contrail coverage [*Rap et al.*, 2010], the model suggests an increase in DTR. This seasonal difference indicates that, similarly to the effect on contrail RF [*Stuber et al.*, 2006; *Rädel and Shine*, 2008; *Rap et al.*, 2010], the air traffic annual cycle also has an effect on

DTR changes. However, considering the fact that these DTR changes correspond to an enhanced contrail experiment, the model indicates that the contrail effect on the DTR is, at least today, very small. In terms of the effect of contrails on DTR at a regional level, we note an increase in DTR over northeast Brazil, South Africa, the Middle-East and the Himalaya-Tibet area, and a decrease in DTR over Western Europe, central Africa and India. These features are consistent with findings from *Hansen et al.* [2005, Figure 15], suggesting that although very small, the contrail effect on DTR simulated by our model may be a physical feature, isolated from the model noise, either caused directly by the enhanced contrails or by the mean temperature change pattern they induce.

[16] Our model also confirms the findings of *Travis et al.* [2007], where observational data showed a significant correlation between the increase in contrail frequency and the cooling of the tropopause over central and eastern USA. Figure 3a shows that linear contrails induce a decrease in the tropopause temperature in northern subtropical regions. This is caused by the warming of the troposphere in these regions leading to an increase of the tropopause height (Figure 3c), making the tropopause colder. This feature seems to be specific to the contrail forcing, as it is not observed in the $2xCO_2$ simulation (Figures 3b and 3d). Besides the cooling of the tropopause in the northern subtropics, the ECON experiment also indicates a tropopause cooling in the Pacific Ocean warm pool, which leads to different water vapour feedbacks compared with the $2xCO_2$ experiment. In fact, although the stratospheric water vapour shows an overall

increase in ECON, this increase is substantially smaller than that in the $2\times CO_2$ simulation. In one decade of the ECON simulation period, we even observed a decrease in stratospheric water vapour in the tropics, which would likely contribute a negative radiative feedback. This, together with the weaker Arctic sea ice feedback in the ECON compared with the $2\times CO_2$ experiment, could be one of the mechanisms that induce the lower climate efficacy of contrails.

4. Discussion and Conclusions

[17] In this study we used the UK Met Office global climate model with *Rap et al.*'s [2010] linear contrail parameterisation in order to investigate the impact of contrails on climate. Our main findings are new estimates for contrail climate sensitivity and efficacy, which are 0.3 K/(Wm^{-2}) and 31%, respectively. Both these values are significantly smaller than the only other estimates currently available, i.e. the ones from *Ponater et al.* [2005] who calculated a contrail climate sensitivity of 0.43 K/(Wm^{-2}), which in their model corresponds to an efficacy of 59%. As a result, our model suggests that although as part of the overall aviation climate impact contrails may remain one of the largest components, they have a limited effect on the Earth's climate. Even in the enhanced contrail simulation (with over 50 times as much persistent contrails) mean temperature, precipitation and DTR are only slightly affected.

[18] The very little surface warming effect of the contrails confirms the findings of *Shine* [2005], *Ponater et al.* [2005], and *Dietmüller et al.* [2008], who concluded that *Minnis et al.*'s [2004] hypothesis of contrails explaining all the continental USA warming between 1971 and 1995 is unrealistic. Another point, also observed by *Ponater et al.* [2005] and *Hansen et al.* [2005], is that the geographical pattern of the contrail surface temperature response is significantly broader than the one of the contrail forcing, being influenced primarily by regional feedbacks rather than the actual forcing.

[19] The global mean contrail effect on precipitation was also found to be very limited, but some interesting regional features, such as the move towards the north of the ITCZ, were observed. Our model simulations suggest that the tropopause is also affected by contrails across the whole northern subtropical region, where the tropopause height is significantly increased relative to other regions, leading to a decrease in its temperature.

[20] Finally, our model supports other recent findings [*Hansen et al.*, 2005; *Dietmüller et al.*, 2008] suggesting that the linear contrail impact on the diurnal temperature range is currently insignificant. However, this result needs to be treated with caution, as our study parameterizes contrails as a thin aerosol layer and does not address the possible role of spreading contrails and aviation-induced cirrus [e.g., *Haywood et al.*, 2009], whose areal coverage may be significantly greater than linear contrails. Observation based studies suggest that the radiative forcing from total aviation induced cirrus is no more than a factor of 10 larger than that for linear contrails [*Forster et al.*, 2007]. In our study, we needed to scale our linear-contrail results by over a factor of 50 to achieve an observable climate response. This scaling is likely larger than needed to account for all aviation induced

cirrus, therefore we can speculate that the climate effect of aviation induced cirrus is also likely to be small.

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