CUED - Engineering Tripos Part IIB 2024-2025 Module Coursework

Module	4A7	Title of report	Net Climate Impact of Contrail Avoidance
Date submitted:	11/12/2024	Assessment for this module is ☒ 100% / ☐ 25% coursework of which this assignment forms 50 %	

UNDERGRADUATE and POST GRADUATE STUDENTS		
Candidate number:	5502A	☒ Undergraduate ☐ Post graduate

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1 Introduction

Contrails formed in the exhaust of aircraft are formed at high altitudes and (at night especially) create a significant warming effect on the planet. Current estimates say that the daily warming impact of aircraft contrails on the environment is greater than the CO_2 emissions for all flights since 1940 [12].

As such, contrail avoidance is becoming an increasingly studied and researched method of decreasing the environmental impacts of aviation in the very short term which is one of it's key advantages over sustainable fuel technology and other low-carbon sources of energy such as liquid Hydrogen or electricity.

The downside of contrail avoidance is the associated fuel penalty due to the change in optimal flight path and conditions to avoid contrail forming regions of the atmosphere. The aim of this work is to quantify the balance between the benefits from reducing contrails and the negatives from increasing fuel burn and to thus assess the feasibility of contrail avoidance for present-day aviation.

2 Approaches, Assumptions and Data Requirements

To quantitively estimate the climate impacts of contrail avoidance, a model was developed in *Python* to calculate the radiative forcing (RF) and the temperature change (ΔT) for every year up to 500 years from the start of the study. The time integrated values of these quantities were also calculated. The model combines an estimate for the RF based on CO_2 emissions, contrails, and CH_4 emissions. The model calculates the RF associated with additional CO_2 emissions due to extra fuel burn to facilitate contrail avoidance (as well as any extra CH_4 emissions if relevant to the fuel used). It then combines this with a negative contribution to the RF due to a reduction in contrails based on a specified percentage of contrails that are avoided.

In undertaking this study, several simplifying assumptions were made to decrease model complexity and so that dependence on large atmospheric models was not required. The key assumptions were assuming that the behaviour of the atmosphere was steady for the next 500 years and that aviation would also not change over the same time period.

If aviation does not grow then the daily energy demand of aviation is constant and is taken as $1.01 * 10^{13}$ MJ [9], [6], [1]. Furthermore the CO_2 emissions per unit energy are constant and given by the EI_{CO_2} of the fuel plus a well-to-pump contribution [15] due to emissions before the fuel is burnt in the plane. For the investigation on liquefied natural gas, the transportation of fuel has an associated EI_{CH_4} which was calculated using data taken from the following paper [8]. See Table 4.

A further assumption was that the total radiative forcing due to contrails was a constant value for all time and was taken as 0.1114 W/m^2 with a constant efficacy factor of 0.42 [12]. The accumulation and decay of the CO_2 and CH_4 emissions were modelled using exponential decay equations (see subsection 6.2 and subsection 6.3) with constant parameters from [11] for CO_2, and [10] for CH_4. These parameters were again assumed to be constant over the time period studied.

The radiative efficiency of CO_2 and CH_4 were again assumed to be constant over the time period with values taken from the IPCC [10] and normalised by the mass of the atmosphere [4] to express them in terms of kg of emission (subsection 6.2 and subsection 6.3) To convert from radiative forcing to a temperature change in the atmosphere, the atmosphere was modelled as a single heat capacity system shown in subsection 6.4.

The final main assumption was that contrail formation with a different fuel or different efficiency would scale with the mixing line gradient of the engine exhaust - denoted G. The equation given in subsection 6.5 was used. This assumption is based on the fact that for contrails to form, the ambient air must be in the Ice Super Saturated Region (ISSR) and that the exhaust must (transiently) cross through the super-saturation region with respect to water. Both conditions on their own are necessary but not sufficient for contrail formation. With a higher mixing line gradient - G, the likelihood of crossing through the liquid super saturated region (LSSR) is increased, but the probability of the ambient air being in the ISSR is unchanged. For simplicity we assume that the total radiative forcing due to all aviation contrails scales linearly with G when evaluating the effect of contrail avoidance on new fuels and higher efficiency engines. This is by no means an accurate assumption but it allows us to give a first order estimate of the suitability of contrail avoidance with new fuels and higher efficiency engines without using large climate models to predict the ISSR and LSSR boundaries.

2.1 Suitability and Effect of Assumptions

Accumulation and decay of radiative forcing due to contrails was neglected as the lifetime of contrails is very short. The maximum lifetime is approximately 24 hours and average e-folding times for contrails is roughly

2 hours [14]. As such it is reasonable to assume that the radiative forcing due to contrails is constant every day given that the number and type of flights is assumed not to change in the future.

Ignoring the vastly predicted growth of aviation in the future is likely to under predict the extent of any response due to contrail avoidance (e.g a predicted decrease in RF will likely be much greater in magnitude and likewise for any predicted increases). However, the baseline CO_2 and contrail emissions are likely to both scale approximately equally with increasing number of flights, therefore the decision on whether a given contrail avoidance plan is positive or negative is very likely to remain unchanged and so for the purpose and scope of this analysis the assumption is reasonable.

The assumption that the decay behaviour and radiative efficiencies of CH_4 and CO_2 is difficult to quantify in terms of accuracy as both the decay and radiative efficiency of each species has been shown to depend on the concentrations of each other as well as other species [10] which is neglected in this analysis. Given the historical trend of decreasing radiative efficiency of CO_2 this would likely continue to decrease in the future and as such would make contrail avoidance appear more favourable.

3 Results

The study was conducted for 3 cases which are as follows: a baseline case based on present day aviation; a step increase in efficiency of 20% over the baseline case; and an immediate switch to operation using liquefied natural gas (LNG). Both of the non-baseline cases assume that the change is immediate and across the entire fleet as mentioned in section 2. The results were graphed for 2 different cases: a constant fuel penalty of 1% and various contrail avoidance rates; and a constant contrail avoidance of 50% and various fuel penalties. The fuel penalty of 1% was chosen as this is at the high end of literature values for fuel burn for contrail avoidance [5]. The value of 50% for the baseline estimated contrail avoidance was chosen based on reports that only 2% of flights are responsible for 80% of contrail RF [13]. It was estimated that attempts would be made to avoid these contrails with the highest RF and if the success rate of that avoidance was 60% then then overall avoidance success rate of contrails would be 48% (approximately 50%). The reason for the low success rate chosen was based on the fact that it can be difficult to predict the location of ISSRs so in some cases the location may be incorrect and diversion may enter a contrail forming region, or the size of the region may be underestimated and the planned avoidance is not successful.

For all cases, 4 metrics were plotted up to 500 years from the start of the contrail avoidance scheme. Any changes in fuel or efficiency were assumed to happen immediately and at year zero. The choice of 500 years was based on IPCC reports from 1990 [7]. However, it is notable that during said report, Houghton et. al. emphasised that the choice of 20, 100 and 500 years for calculating climate metrics over, was an arbitrary choice. Therefore for the following work I have chosen to include full graphical time history of each metric instead of solely values at the above time horizons.

The choice of both time horizon and climate impact metric are equally and extremely important in terms of the influence they hold on policy makers. The choice of climate impact metric is a trade-off between scientific certainty in the value calculated, and relevance to climate policies and policy-makers.

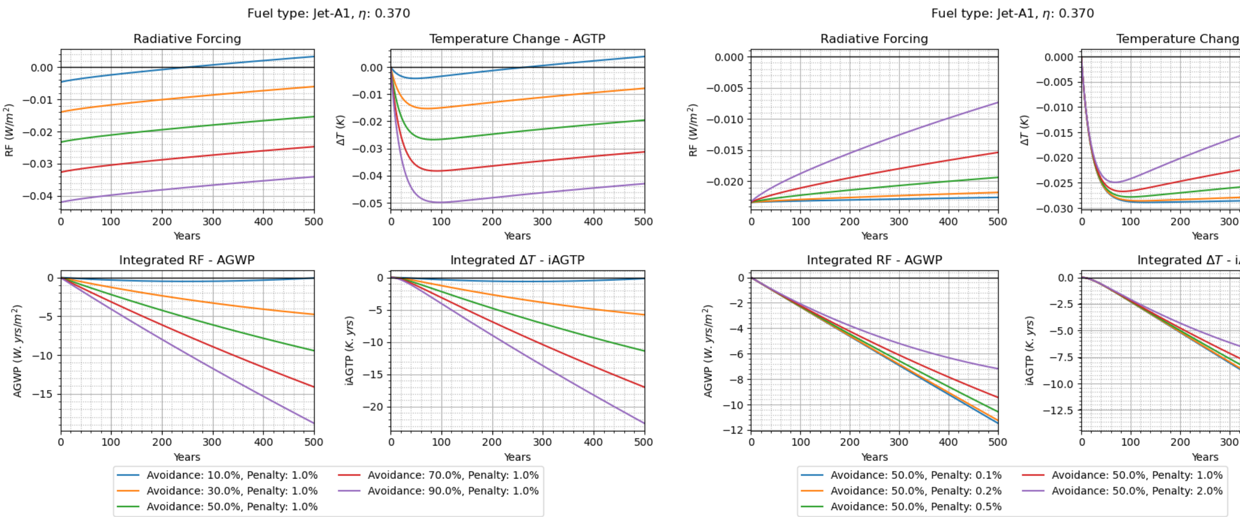
Given the highly emphasised target of remaining below 1.5°C of warming vs pre-industrial levels by 2050, policy makers and climate policies focus heavily on end-point metrics such as Global Temperature Potential or temperature change (which is considered in this report). Not only does this metric closely align with policy but it is much easier to understand for the average person not familiar with climate science. However, it is calculated with less certainty than radiative forcing because of the influence of multiple heat-sinks in the earth's temperature response such as the deep ocean and therefore relies on either carefully calibrated models with multiple heat-sinks and time constants, or less accurate models using a single calibrated heat-sink as done in this work. Radiative forcing, on the other hand, is a far more accurate measure to calculate and displays the instantaneous effect on the environment compared to an end-point metric. However, it is much less intuitive at first glance; the average person is unlikely to understand what a benefit of $1mW/m^2$ means as compared to a temperature change of say $1mK$. As such radiative forcing is often less considered for policy decisions despite it's increased certainty.

Time horizon choice is another key factor to consider especially when influencing policy decisions. As mentioned above, short term policies such as limiting global temperature rise to 1.5°C by 2050 places emphasis on the 20 year time horizon. Economic discount rates vary between governments with highly developed nations often but not always having lower discount rates. A higher discount rate reduces the value of future costs or benefits and as such places higher impact on shorter time horizons and vice versa. The choice of time horizon also favours the impacts of certain emissions. For example, comparing the CO_2 decay equation Equation 1 with that for CH_4 Equation 2, we can see that 22% of emitted CO_2 remains in the atmosphere for at least 1000 years, continuing to increase RF. On the other hand, CH_4 decays comparatively very quickly and by 50 years after the emission only 1.4% remains. As such, short time horizons place more impact on emissions of methane rather than carbon dioxide.

3.1 Baseline Case

Avoidance	Penalty	RF (W/m^2)			*Delta*T (K)		
		20 yrs	100 yrs	500 yrs	20 yrs	100 yrs	500 yrs
0.5	0.001	-0.023	-0.023	-0.023	-0.018	-0.029	-0.028
	0.002	-0.023	-0.023	-0.022	-0.018	-0.029	-0.027
	0.005	-0.023	-0.022	-0.019	-0.018	-0.028	-0.024
	0.01	-0.023	-0.021	-0.015	-0.018	-0.027	-0.02
	0.02	-0.022	-0.019	-0.007	-0.017	-0.024	-0.01

Table 1: Time horizon results for Jet-A1 case



(a) Dependence on avoidance rate

(b) Dependence on additional fuel burn

Figure 1: Comparison of contrail avoidance and fuel burn penalty for baseline Jet-A1

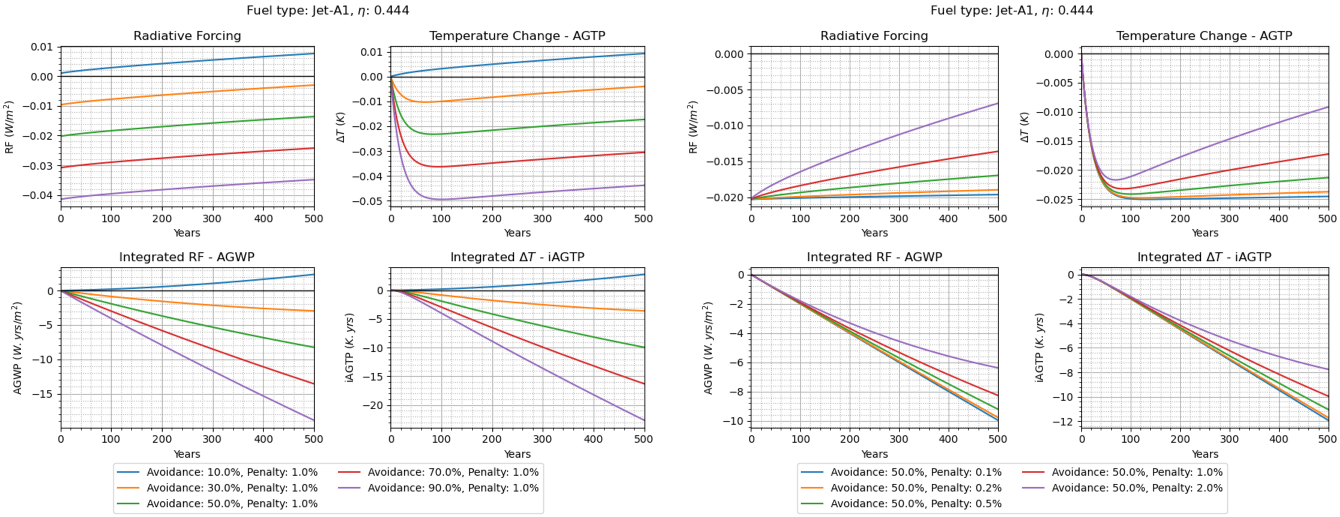
It was found that for the present-day model of global aviation, with an assumed efficiency of 0.37 [2], contrail avoidance was a large improvement for a wide range of scenarios. For a fleet wide fuel burn penalty of 1% due to contrail avoidance, just a 30% avoidance success rate was sufficient for the radiative forcing and temperature change to be negative for at least 500 years which implies that contrail avoidance has a significant positive impact on the climate for today's fuel and engines used in aviation.

Assuming a contrail avoidance success rate of 50%, a fleet-wide fuel penalty of even 2% still kept RF and temperature change negative over the 500 year time span modelled.

3.2 Increased Efficiency

Avoidance	Penalty	RF (W/m^2)			*Delta*T (K)		
		20 yrs	100 yrs	500 yrs	20 yrs	100 yrs	500 yrs
0.5	0.001	-0.02	-0.02	-0.02	-0.016	-0.025	-0.025
	0.002	-0.02	-0.02	-0.019	-0.016	-0.025	-0.024
	0.005	-0.02	-0.019	-0.017	-0.016	-0.024	-0.021
	0.01	-0.02	-0.018	-0.014	-0.015	-0.023	-0.017
	0.02	-0.019	-0.016	-0.007	-0.015	-0.021	-0.009

Table 2: Time horizon results for high efficiency Jet-A1 case



(a) Dependence on avoidance rate

(b) Dependence on additional fuel burn

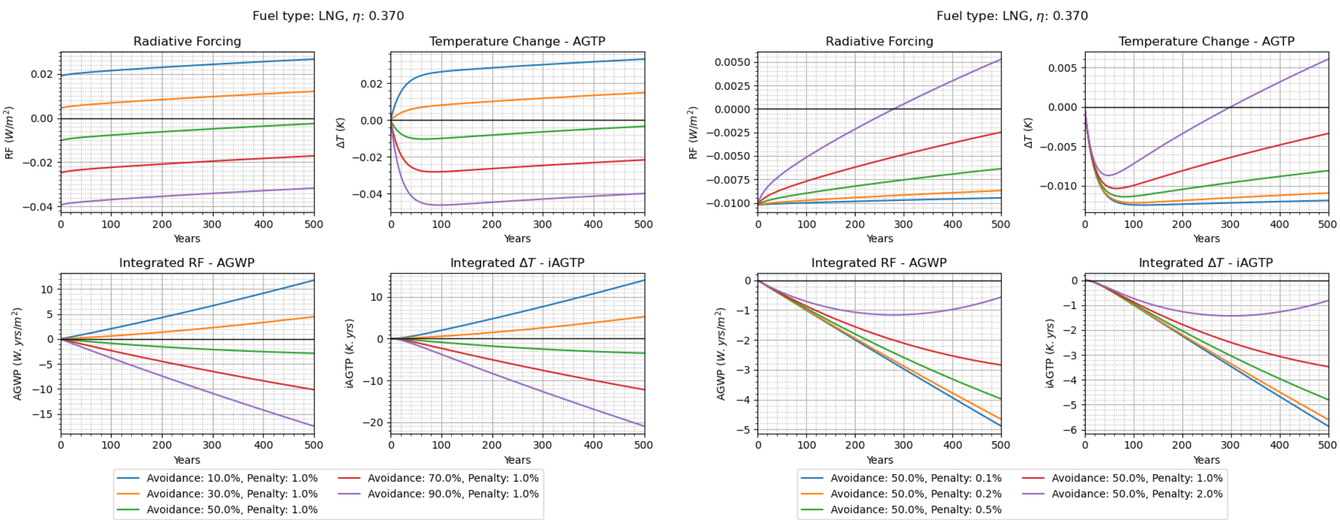
Figure 2: Comparison of contrail avoidance and fuel burn penalty for increased efficiency Jet-A1

For a step increase in aviation engine efficiency of 20% (from 0.370 to 0.444), the results are very similar to the baseline case using jet-A1, but with all values increased slightly. However, contrail avoidance of 30% with a 1% fuel penalty still has a positive climate impact over 500 years, but a slightly smaller impact than with the lower efficiency engines used currently by the global fleet.

3.3 A switch to Liquefied Natural Gas

Avoidance	Penalty	RF (W/m^2)			$Delta$T (K)		
		20 yrs	100 yrs	500 yrs	20 yrs	100 yrs	500 yrs
	0.001	-0.01	-0.01	-0.009	-0.008	-0.012	-0.012
	0.002	-0.01	-0.01	-0.009	-0.008	-0.012	-0.011
0.5	0.005	-0.01	-0.009	-0.006	-0.008	-0.011	-0.008
	0.01	-0.009	-0.008	-0.002	-0.007	-0.01	-0.003
	0.02	-0.008	-0.005	0.005	-0.007	-0.007	0.006

Table 3: Time horizon results for LNG



(a) Dependence on avoidance rate

(b) Dependence on additional fuel burn

Figure 3: Comparison of contrail avoidance and fuel burn penalty for Liquefied Natural Gas

A global fleet fuelled entirely by liquefied natural gas (LNG) has a much more dramatic change than an increase in efficiency. The high well-to-pump emissions of methane for LNG (see subsection 6.1) increase the climate consequences of the assumed fuel burn penalty. As such, for a 1% fuel burn penalty, a contrail avoidance success rate of 50% is required to keep RF and ΔT negative over 500 years - 20% higher than for Jet-A1 at the same efficiency. Similarly, fuel burn penalties higher than 1% for an avoidance success rate of 50% lead to RF and ΔT exceeding 0. For a penalty of 2% this occurs at approximately 300 years from today, however the integrated metrics remain negative over the 500 years even with this higher penalty due to the short term cooling effect of contrail avoidance before the effects of methane and carbon dioxide accumulation in the atmosphere build up.

4 Discussion and Conclusions

The fuel penalties used in the above analysis were for the full fleet which likely represents a significant overestimation. J.A Elmourad showed (in Figure 4 that solely considering contrail forming flights, contrails could be avoided with a 100% success rate with only a 1.4% of extra fuel burn. When averaged over the entire fleet this results in a fuel burn penalty of just 0.6% for the whole fleet to avoid 100% of contrails. In reality some contrails are cooling depending on geographical location, the surface albedo below, and the time of day. With advancements in contrail prediction and modelling, the cooling contrails would not need to be avoided which would further lower the fuel burn penalty (as Elmourad illustrates by only avoiding night-time contrails which are always warming). The work by Elmourad neglects any mistakes in contrail avoidance due to inaccuracies in the predictions of ISSRs in the atmosphere. This would lower the success rate of contrail avoidance but it is beyond the scope of this work to estimate what that error might be. With improvements in satellite imagery and atmospheric modelling to predict ISSRs, the success rate of avoidance will tend to the theoretical maximum.

Considering these results, a 1% fuel burn penalty over the entire fleet to avoid only 50% of contrails is quite a large overestimation of fuel burn.

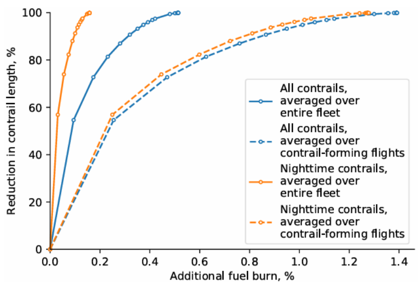


Figure 4: Contrail avoidance against fuel penalty from J.A Elmourad [5]

For the three cases tested, considering an overestimated fuel burn penalty of 1%, and a contrail avoidance success rate of 50%, the total RF and ΔT, as well as the integrated values of these quantities, are negative for all years up to 500 years. The baseline case had the largest impact due to contrail avoidance ($\Delta T@500yrs = -0.020K$), with higher efficiency engines decreasing the impact slightly ($\Delta T@500yrs = -0.017K$), and LNG fuel decreasing the impact significantly ($\Delta T@500yrs = -0.003K$). The main reason for the decrease in efficacy of contrail avoidance when using LNG is the high well to pump emissions of methane when shipping natural gas which means that fuel burn penalty is accentuated by the emissions of a greenhouse gas with a radiative efficiency nearly 30 times greater than CO_2 per ppb of GHG. The graphs of Figure 1, Figure 2, and Figure 3, show clearly that shorter time horizons favour contrail avoidance schemes as the effects of emissions do not build up as significantly whereas the longer time horizons place more impact on the extra emissions due to the fuel burn penalty of changing flight path to avoid ISSRs (contrail forming regions) in the atmosphere. Borella et. al. [3] found similarly that "time-integrated metrics defined on a short time horizon, like AGWP20 or ATR20, put more weight on contrail cirrus, while endpoint metrics on a long time horizon, like AGTP100, put more weight on CO2. (p. 16)".

To conclude, for a sensible (and arguably low) contrail avoidance success rate of 50%, and a high fleet wide fuel burn penalty of 1%, contrail avoidance has a positive climate impact up to at least 500 years in the future. Given that the technology used in aviation is likely to change significantly over 500 years towards carbon neutral fuels, the benefits of contrail avoidance will only increase. Additionally, contrail avoidance, even with low success rates and high fuel penalties, offers significant short term temperature decreases over the scale of 20-100 years which is likely to drive global policy decision in favour of contrail avoidance given the aims to keep global temperature rise to just 1.5°C by the end of the next 25 years.

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6 Appendices

6.1 Fuel Properties

Fuel	EI_{CO_2} burn kg/kg	EI_{CO_2} WTP kg/kg	EI_{CH_4} burn kg/kg	EI_{CH_4} WTP kg/kg	EI_{H_2O} kg/kg	LCV MJ/kg	η
Jet-A1	3.14	0.86 [15]	0.0	0.0	1.28	43.2 [1]	0.37 [2]
LNG	2.75	1.366 [8]	0.0	0.045 [8]	2.25	48.6 [8]	0.37

Table 4: Fuel Data used

6.2 Carbon Dioxide Properties

$$\mathrm{IRF}(t) = a_0 + \sum_{i=1}^{3} a_i \cdot \exp\left(-\frac{t}{\tau_i}\right) \quad \text{for } 0 \leq t \leq 1000\,\mathrm{yr} \tag{1}$$

a_0	a_1	a_2	a_3	τ_1	τ_2	τ_3
0.2173	0.2240	0.2824	0.2763	394.4	36.54	4.304

Table 5: Decay of CO_2 from [11]

Radiative Efficiency (W/m^2 per ppb)
$1.33 * 10^-5$ [10]

6.3 Methane Properties

$$\mathrm{IRF}(t) = \exp\left(-\frac{t}{\tau}\right) \tag{2}$$

τ (years)
11.8

Table 6: Decay of CH_4 from [10]

Radiative Efficiency (W/m^2 per ppb)
$3.88 * 10^-4$ [10]

6.4 Temperature Response due to Radiative Forcing

$$\frac{dT}{dt} = \frac{\mathrm{RF}(t) - \frac{1}{\lambda}(T(t) - T_0)}{C} \tag{3}$$

C ($W.yr/m^2$ per K)	$\frac{1}{\lambda}$ (W/m^2 per K)
17	0.8

Table 7: Atmospheric temperature response due to radiative forcing

6.5 Mixing Line Gradient - G

$$G = \frac{P \cdot EI_{H_2O} \cdot C_P}{\varepsilon \cdot LCV \cdot (1 - \eta)} \tag{4}$$