4A7 Aviation and the Environment [Lectures 5-6]

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Topics

- Climate Change Effects and Valuation (ctd)
- Climate Metrics
- Formation
- Persistence
- Evolution
- Impacts
- Project and Report

Contrails

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Discount Rate

- The discount rate is the function at which future costs (or benefits) are valued relative to costs (or benefits) that accrue today.

- The social discount rate is dominated by three phenomena: the investment rate of return, the rate of time preference, and the diminishing marginal utility of wealth.

2 – 7%

- Climate impacts may be different from some other impacts in that they can be irreversible or the burden of their impacts may be borne by future generations.

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Discounting

- Gross damages can be expressed as a stream of future damages.

$$D(t) = a\,[\Delta T(t)]^2\,GDP(t)$$

- To understand the relative impact of future damage, convert to present damages. Policy assessments often choose constant discount rates (exponential discounting).

$$\text{Present value} = PV = D(t) \times \frac{1}{(1+r)^t}$$

e.g. $r = 0.03$ (3% discount rate)

$t = 1, 2, 3 \dots$ yrs

- Summing a stream of present values will indicate total costs.

$$\text{Net PV} = NPV = \sum_{t=0}^{\infty} PV(t)$$

- The discount rate is subject to both uncertainty and preference.

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Concept Question

The United Nation proposes a CO_2 emissions reduction policy to be enacted in the next year. Each member nation sends the policy proposal to its own economists to decide whether or not the policy is a good idea. Three of the countries examining this policy are:

- A: developed country with the best economy,
- B: a developing country with rapidly growing industry
- C: a developing island nation with eco-tourism as only industry.

How would you expect the discount rates on climate damages in the independent analyses to compare?

1. ~~A > B > C~~
2. ~~B > A > C~~
3. ~~C > A > B~~
4. They should all be the same.

Highest: B : developing industry
Middle : A
Lowest : C island nation

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TH = 20, 50, 100, 500 yr etc.

Climate Metrics For Emissions

	Instantaneous	Integrated
• Radiative Balance	$RF(t)$	$AGWP = \int_0^{TH} RF(t)\,dt$
	Radiative Forcing	Absolute Global Warming Potential
• Temperature	$AGTP = \Delta T(t)$	$iAGTP = \int_0^{TH} \Delta T(t)\,dt$
	Absolute Global Temperature Potential	Integrated AGTP

The Social Cost of Carbon (SCC) | UK ~ £250/t

	Discount Rate and Statistic			
Year	**5% Average**	**3% Average**	**2.5% Average**	**3% 95th percentile**
2015	$11	$36	$56	$105
2020	$12	$42	$62	$123
2025	$14	$46	$68	$138
2030	$16	$50	$73	$152
2035	$18	$55	$78	$168
2040	$21	$60	$84	$183
2045	$23	$64	$89	$197
2050	$26	$69	$95	$212

US Interagency Working Group SCC

CO_2 as a reference gas $\rightarrow$ $CO_2(e)$, CO_2e,

- Because of CO_2's importance as an anthropogenic greenhouse gas, most other climate forcers are expressed as CO_2 equivalents (CO2e)
- CO_2 equivalent metrics are taken by dividing the absolute metric by the CO_2 metric given the same time horizon and dropping the word "absolute" from the nomenclature.

$$GWP_{TH} = \frac{\int_0^{TH} RF_x(t)\,dt}{\int_0^{TH} RF_{CO_2}(t)\,dt}$$

for 1 kg of X and CO_2

- The most common metric for CO_2 equivalence is the GWP(100)

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Initial conditions

As far as contrails are concerned, the aircraft emits:

- Water (H_2O), $EI(H_2O)$ from H:C in fuel
- Soot (BC), $EI_N(BC)$ from measurement
  ↑ number

The exhaust plume is hot and moist. As it spreads out behind the aircraft it entrains colder and dryer ambient air, dropping the temperature and humidity in the plume.

If it gets cold enough and/or humid enough in the exhaust plume for water to condense on the ice nuclei then a contrail can form. This may or may not persist.

The number of ice nuclei does not affect whether or not a contrail forms or persists, but does influence its properties.

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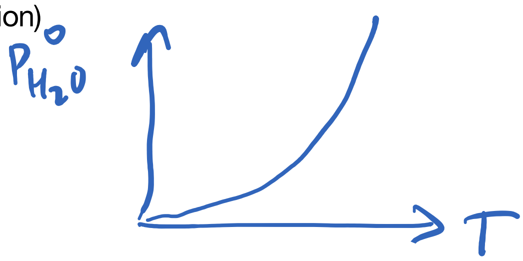
Dalton's law $\underbrace{p_x}_{\text{partial pressure}} = \underbrace{p}_{\text{pressure}}\, y_x$ ← mole fraction

Relative humidity (RH) with respect to water

- Water vapor condenses onto liquid water droplets at a relative humidity with respect to liquid water larger than 100%:

$$RH|_w = \frac{p_{H_2O}}{p^o_{H_2O}|_w}$$

- Saturation pressure with respect to liquid water is the maximum pressure of water vapor before it condenses onto droplets: this depends exponentially with temperature (Clausius-Clapeyron relation)



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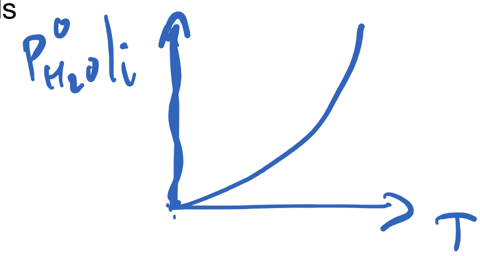
RH with respect to ice

- Water vapor condenses onto ice crystals at a relative humidity with respect to ice larger than 100%:

$$RH_i = \frac{P_{H_2O}}{P^o_{H_2O}\big|_i}$$

- Saturation pressure with respect to ice is the maximum pressure of water vapor before it condenses onto crystals



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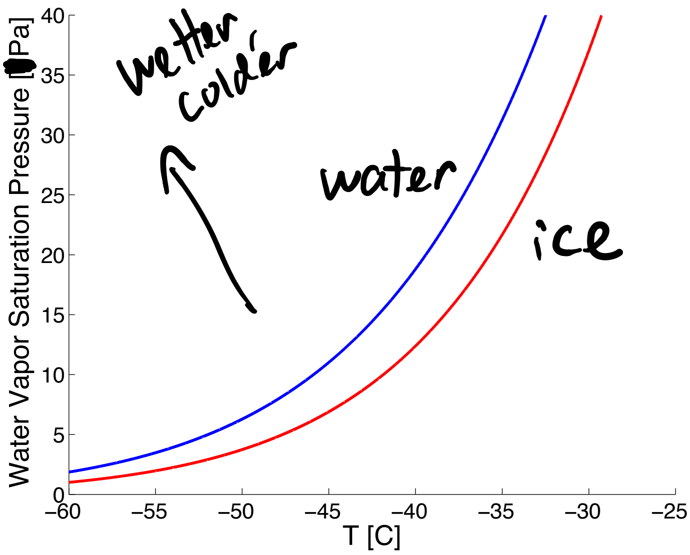
Saturation curves for water and ice



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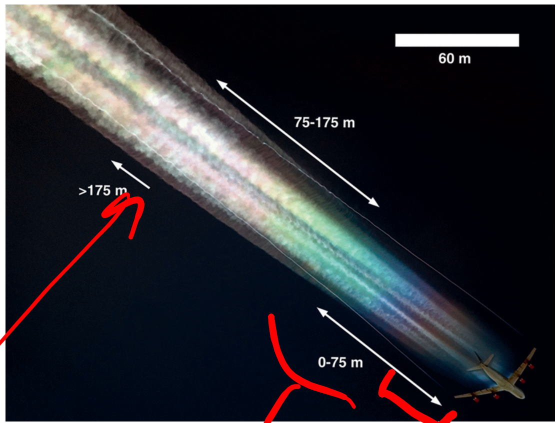
Contrail formation

- Contrails are generated in the aircraft wake if the mixture of exhaust gases and ambient air transiently reaches or surpasses saturation with respect to liquid water
- In this condition, water vapor can condense on soot and volatile particles in the exhaust plume to form the liquid droplets
- Contrails form about one wingspan downstream the aircraft: before, the gaseous exhaust is too hot to condense into droplets



ice liquid gaseous

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- In order for a contrail to form, the relative humidity with respect to liquid water must be transiently above 100% (liquid-supersaturated condition)

locally, transiently $RH_w \geq 100\%$ (in the plume)

- High temperatures give a too high saturation vapor pressure, thus contrails cannot form too close to the exhaust of the aircraft
- At the low temperatures of the upper troposphere, liquid droplets do not last long: they either evaporate or condense into ice crystals
- Contrail persistence requires condensation of water droplet into ice: the condition for this is a relative humidity with respect to ice RH_i to be above 100% (ice-supersaturation)

ultimately $RH_i \geq 100\%$ in the ambient for persistence

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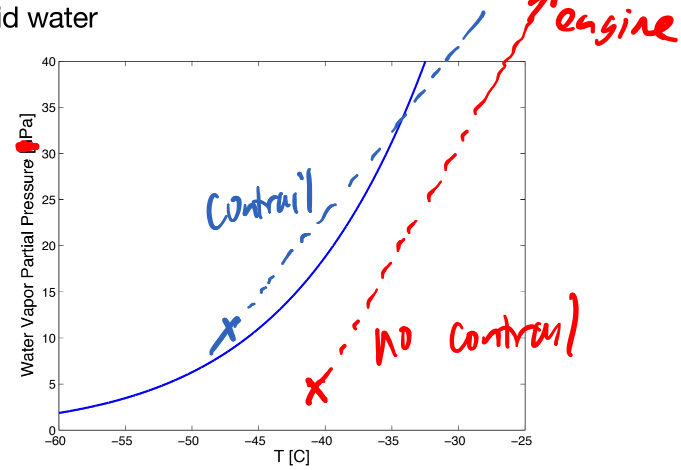
Schmidt-Appleman criterion for short (or long) lived contrail

- Schmidt-Appleman criterion (SAC) says that contrails are generated in the aircraft wake if the mixture of exhaust gases and ambient air transiently reaches or surpasses saturation with respect to liquid water



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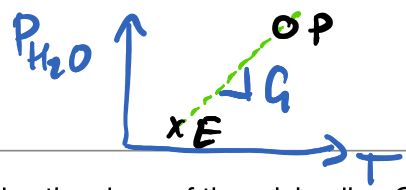
Slope of mixing line



Here we will derive from first principles the slope of the mixing line *G*.

Take 1 kg of fuel (combusted)   N−1 kg of air ⇒ N kg parcel

m_P = water mass fraction in plume (at P)

m_E = " " " " environment (ambient)

$$m_P = \frac{EI + (N-1)\,m_E}{N} \qquad EI = EI(H_2O)$$

$$\Delta m = m_P - m_E = \frac{EI - m_E}{N} \approx \frac{EI}{N}$$

$(1-\eta_{\text{thermal}})$ LCV = heating of exhaust plume per kg of fuel

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$$\Delta h = h_P - h_E = \frac{LCV(1-\eta) - \cancel{h_E}}{N} \quad \text{neglect}$$

$$\Rightarrow \Delta h = \frac{(1-\eta)LCV}{N} \approx c_p \Delta T$$

$$P_{H_2O} = p\, Y_{H_2O} \leftarrow \text{mol fraction}$$

$$= p\, m_P \frac{M_{air}}{M_{H_2O}}$$

$$\text{Set } \varepsilon = M_{H_2O} / M_{air} = 0.622$$

$$\Rightarrow P_{H_2O} = p\, m_P / \varepsilon$$

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$$G = \frac{\Delta P_{H_2O}}{\Delta T} = \frac{p\, \Delta m}{\varepsilon\, \Delta h / c_p}$$

$$= \frac{c_p\, p\, EI / N}{\varepsilon\, LCV\, (1-\eta)/N}$$

$$\Rightarrow \boxed{G = \frac{p\, EI_{H_2O}\, c_p}{\varepsilon\, LCV\, (1-\eta)}}$$

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Role of soot

C

- Soot particles are understood to form the ice nuclei (IN) for contrails
- It is possible that other emissions (such as sulfuric acid) may also contribute to contrail ice nucleation
- Total water emitted is unaffected by soot emissions
- Many smaller ice crystals leads to a greater optical depth than fewer bigger ice crystals

Higher radiative effects

High $EI_N(BC)$ | Low $EI_N(BC)$

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Role of $EI(H_2O)$

$EI_{SAF} \sim 1.1 \times EI_{Jet\ A1}$

- $EI(H_2O)$ is related to the H:C ratio in the fuel
- Several possible alternative liquid fuels have higher values of $EI(H_2O)$

LH_2, LNG (CH_4) $\Rightarrow$ Increase $EI(H_2O)$

- In addition, paraffinic biofuels have a higher $EI(H_2O)$

SAF

- These will tend to increase contrail formation

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Contrail persistence

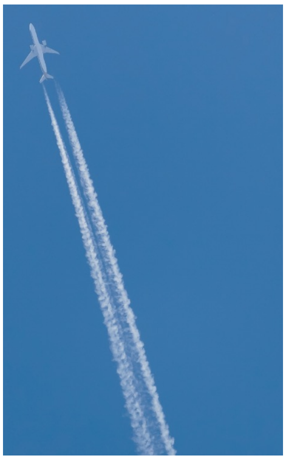
Only persistent contrails matter climatically

- Even if the Schmidt-Appleman criterion is satisfied, a contrail might only form briefly before evaporating

non-persisting

evaporation

water droplets



water droplets

freezing

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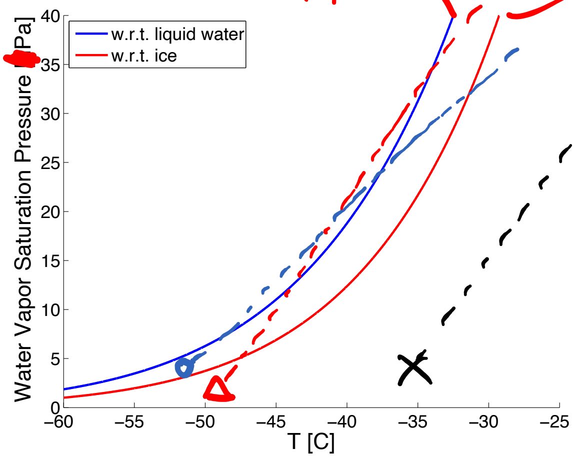
Persistence condition

ISS(R) ice super-saturated (region)

- Contrails only persist if they are formed in a part of the atmosphere that is locally supersaturated with respect to ice

Persistent contrail condition = SAC + ISSR



x no contrail

Δ non-persisting contrail

o persistent contrail

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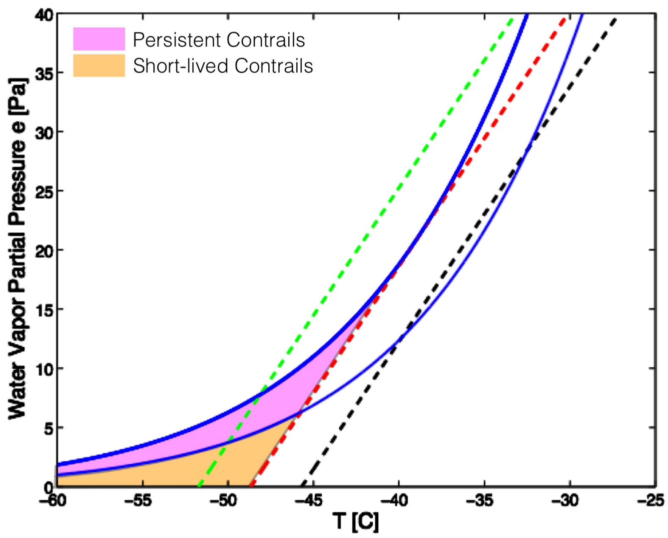
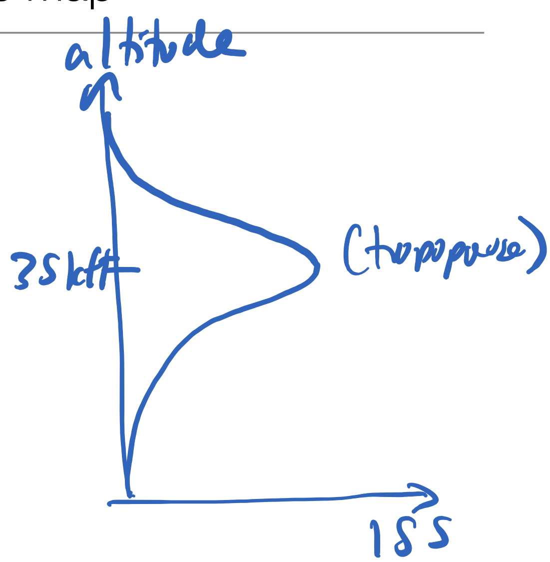
Contrail formation and persistence map





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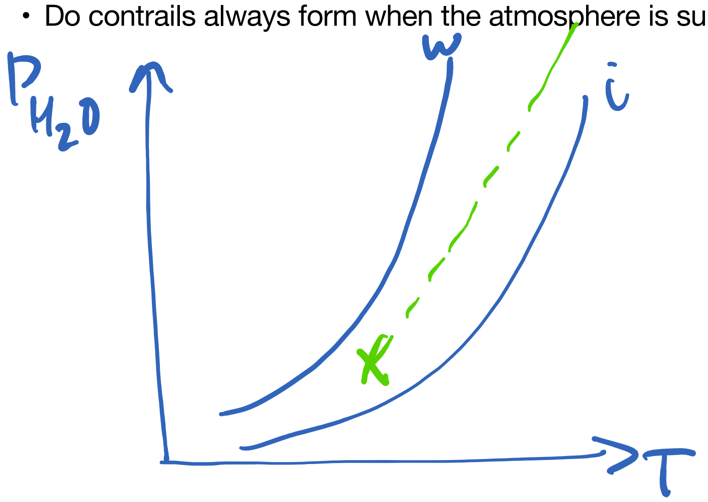
Concept question

- Do contrails always form when the atmosphere is supersaturated with respect to ice?



NO, but ~90% of ISSRs also satisfy SAC

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Wake vortex effects and dispersion

- Contrails experience downwash from the aircraft
- The contrails also get wrapped around in the trailing vortices
- In addition, the low pressure core of the trailing vortices can trap the contrails
- These vortices eventually break-up

Crow/Widnall instabilities

- The initial mixing of the plume is a jet
- Later jet mixing becomes negligible, and instead ambient turbulence causes continued growth of the contrail

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Microphysical properties

- Contrail ice crystals also fall relative to the bulk air surrounding them, which can mean they fall out of supersaturated air

$D \sim r^2$

$w \sim r^3$

$\Rightarrow$ large crystals fall faster (e.g. SAF)

- Over time contrails gain water from the atmosphere by deposition
- Contrails with larger surface area gain more water mass (larger surface area), but contrails with larger diameter fall out faster
- Crystals also aggregate by collision

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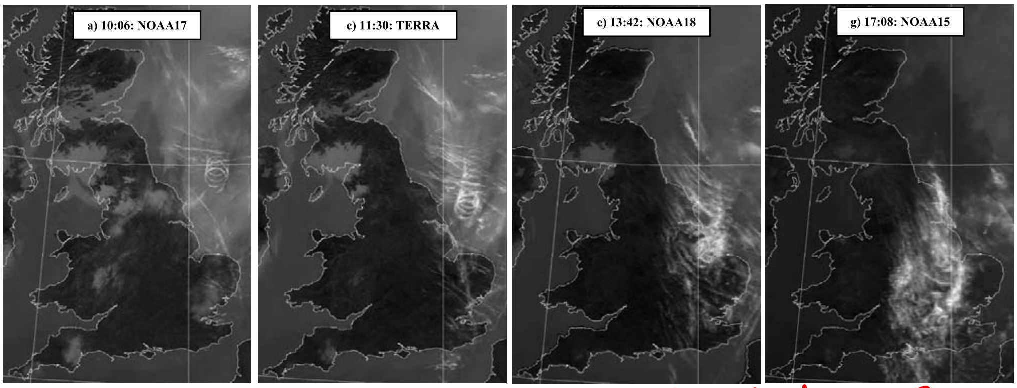
Contrail-cirrus

"linear contrail"

AIC (aircraft induced cloudiness)

"contrail-cirrus"

- Contrails gradually evolve into "contrail-cirrus"
- This can be indistinguishable from natural cirrus



→ most H_2O from atmos.

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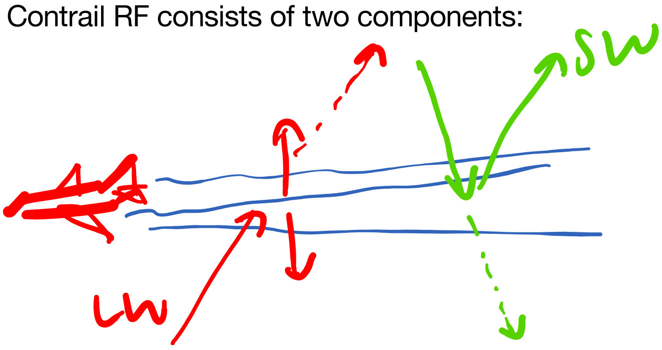
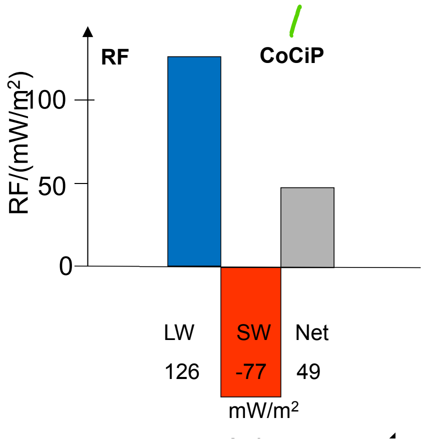
Longwave and shortwave forcing

- Contrail RF consists of two components:



- Most estimates put these as warming on net

a model



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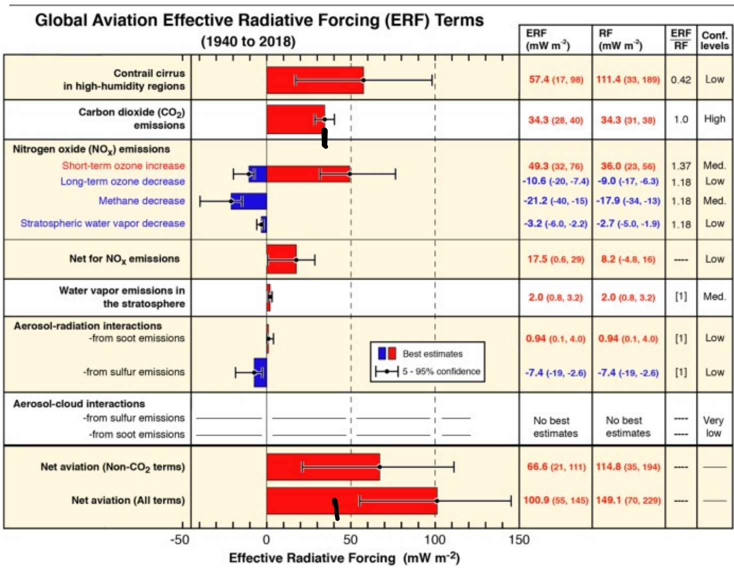
Contrail RF relative to other aviation forcers



scale RF from this

(but CO_2 has "memory")

D.S. Lee et al., The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018, Atmospheric Environment, 2020

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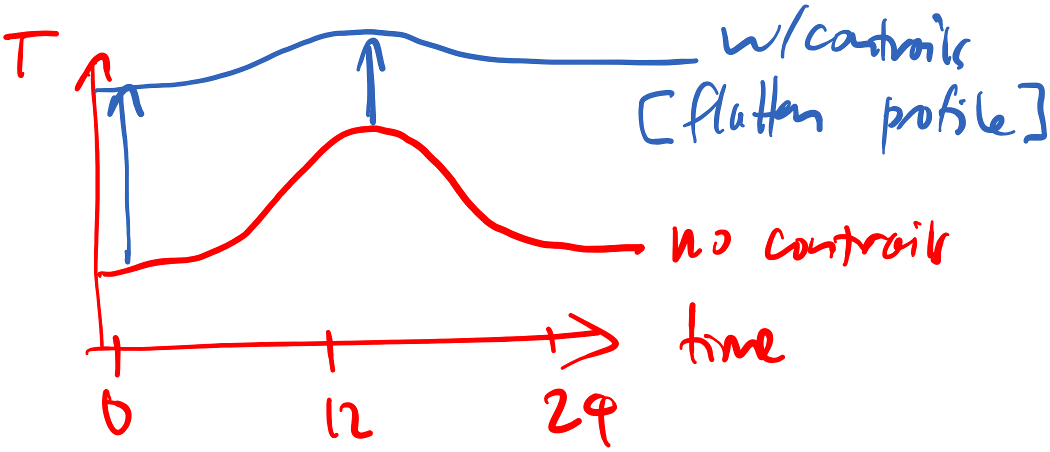
Concept question

- How does the day/night temperate change with the introduction of contrails?



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Project

- The aim of the project is to **evaluate the net climate impact of contrail avoidance**
- The evaluation should be in terms of:
  - Radiative forcing and temperature change over time; and time integrated RF and temperature change out to time horizons of 20, 100, and 500 years; any other climate metrics that you chose to apply
  - As a function of the assumed fuel penalty associated with avoidance (0.1, 0.5, 1, 2)%
- Undertake this assessment for a baseline case and under these variations:

Jet A1

  - If the aircraft fleet is assumed to instead be fueled by liquified natural gas (LNG), which you can approximate as methane (CH_4)
  - If the gas turbines powering the fleet have a higher thermal efficiency (by an amount of your choosing)

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Assumptions

- A key part of the project entails making appropriate simplifying assumptions – make these with justification
- Suggested assumptions:
  - Scale contrail RF from scientific assessments on a per unit fuel burn basis
  - That contrail formation for a different fuel or efficiency scales with G (the contrail mixing line gradient), but note that this is an upper bound since the frequency of ISS regions in the atmosphere is not affected by G
  - Let the entire aircraft fleet change instantly (to higher efficiency or LNG-fueled)
  - Neglect growth in the fleet and keep fuel energy use constant

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Report

- Start date is today - **Due at 4pm on 11 December (upload to Moodle)**
- Remember that the report should not have identifying information
- Page limit for the main report is 5 pages
  - The page limit does include figures
  - You should include references (not included in the page limit)
  - Optionally you can include appendices beyond the page limit for technical information or calculations
- Structure as a technical or scientific paper
- In general information used should be derived from the scientific literature or credible industry/government reports that you reference, not just lecture notes

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Marking

- Marks will be awarded approximately equally for
  - Appropriate simplifying assumptions, analytical approaches, and (referenced) data selection
  - The quality of the technical writing, structure, and visual presentation
  - The technical/scientific validity and insight
- The marks available represent 50% of the total available for 4A7 – ie. 30/60

End of 4A7 lectures

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