# 4A7 Aviation and the Environment [Lectures 3-4]

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## Topics

- Aircraft $CO_2$ emissions
- Greenhouse Effect
- Greenhouse Gases and Climate Change
- Other Drivers of the Greenhouse Effect
- Emissions-to-Impact Pathway
- Earth's Temperature Response
- Climate Change Effects and Valuation

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## Concept question

For every kilogram of fuel burned by an aircraft engine, is the total mass of $CO_2$ emitted by the engine more or less than 1 kg?

mass $CO_2$ > mass C

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## Emissions index (EI) $\frac{\text{g of X}}{\text{kg of fuel}}$ $EI(X)$, $EI_X$, X EI

- Aircraft emissions are presented on a normalized basis as a function of thrust ("indexed")
- For some emissions there is no thrust setting dependency

$CO_2$ $H_2O$ $SO_x$

- The emission rate of X in g is given by

$$\underbrace{E(X)}_{g/s} = \underbrace{\dot{m}_f}_{kg/s} \; \underset{\frac{\text{g of X}}{\text{kg of fuel}}}{EI(X)}$$

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## Deriving EI($CO_2$)

- The $CO_2$ EI is not a function of thrust setting and only of the fuel properties
- This considers only the wake emissions (and not the lifecycle emissions)

Avg. Jet Fuel $C_{12.5}H_{24.4}$

Molar masses: M(H) M(12)

(g/mol) M(X) M(O) = 16 M($CO_2$) = 44

$$\text{carbon mass fr. in fuel} = \frac{12.5 \times 12}{12.5 \times 12 + 24.4 \times 1} = 86\%$$

$$\Rightarrow EI(CO_2) = \frac{M(CO_2)}{M(C)} \times 0.86 = 3.154 \text{ kg/kg}$$

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## $CO_2$ emissions for an A320 mission

- Neglect LTO portion for in-lecture example, but in general add up the phases of flight plus any holding time

Fuel burn = 78t − 62.4t = 15.6 t of fuel

$\Rightarrow CO_2 = 15.6 \times 3.154 = 49.2$t of $CO_2$

- Per passenger for the example flight this equates to:

150 seats, 80% load → 120 pax

$CO_2$/pax = 410 kg

$$CO_2/\text{pax.km} = \frac{410}{6500} \times 1000 = 63 \frac{g}{\text{pax.km}}$$

cf. cars ~ 123 g/km

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## Heat Transfer Refresher

Three fundamental modes of heat transfer:

| | Flux | Relevant area |
|---|---|---|
| Convective | $q = h(T_s - T_\infty)$ | $A_s$ (surface) |
| Conductive | $q = -\lambda \frac{dT}{dx}$ | $A_x$ (cross-section) |
| Radiative | $q = \varepsilon \sigma T^4$ | $A_s$ |

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## Temperature of the Earth: No Greenhouse Effect

The average temperature of the earth (assuming no greenhouse effect) can be calculated from basic heat transfer equations.


1. Assume no internal heat generation.
2. Assume the earth's surface is in thermal equilibrium.
3. Assume that the earth is a perfect sphere.
4. Assume the sun is close to a blackbody.
5. Assume the earth is close to a blackbody, and that ice/snow is close to perfectly reflective

$P_{out} = A \sigma \varepsilon T^4$

Net albedo

$\alpha = 0.28$

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## Temperature of Earth (continued)

- Solar Constant: $F_S$ = 1368 W/m² (at 1 Astronomical Unit)
- Stefan-Boltzman Constant: $\sigma = 5.67*10^{-8}$ W/(m²K⁴)

$(\varepsilon_{EARTH} = 1)$


$$\pi R_E^2 F_S (1-\alpha) = 4\pi R_E^2 \sigma T_E^4$$

$$\Rightarrow T_E = \left[\frac{F_S(1-\alpha)}{4\sigma}\right]^{1/4} = 255\ K = -18°C$$

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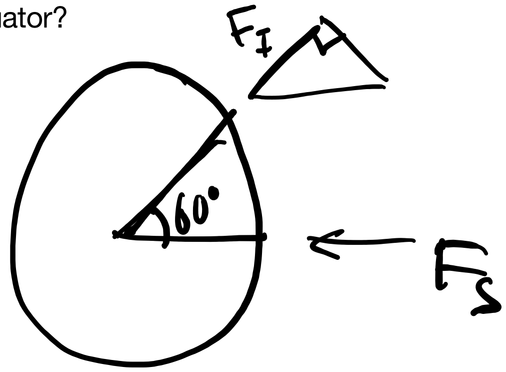
## Concept question

If the earth did not tilt, but instead rotated completely perpendicular to its axis of orbit, what fraction of energy would be incident on the 60th latitude (~ Helsinki, Juneau) relative to the equator?




$$F_I = F_S \cos 60^\circ$$

$$\Rightarrow F_I = \frac{1}{2} F_S$$

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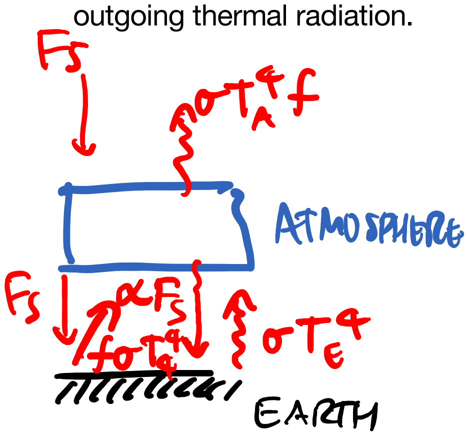
Kirchoff's law $\epsilon_\lambda = \alpha_\lambda = f$ = emissivity = absorbtivity

## Temperature of the Earth: 1-Layer Atmosphere [1]

- Assume a single layer isothermal atmosphere.
- Assume atmosphere is transparent to solar radiation but absorbs a fraction ($f$ = .77) of outgoing thermal radiation.




$$F_{sw}\, 4\pi R^2 = F_s (1-\alpha)\, \pi R^2$$

$$\Rightarrow \text{Incoming: } F_{sw} = \frac{1}{4}(1-\alpha) F_s$$

$$\text{Outgoing: } F_{LW} = \sigma\left[f T_A^4 + (1-f) T_E^4\right]$$

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## Temperature of the Earth: 1-Layer Atmosphere [2]

System Energy Balance: $\frac{F_S(1-\alpha)}{4} = \sigma\left[f T_A^4 + (1-f) T_E^4\right]$

Atmosphere Energy Balance: $f\sigma T_E^4 = 2 f \sigma T_A^4$

$\Rightarrow T_A^4 = \frac{1}{2} T_E^4$

Substituting:

$$\frac{F_S(1-\alpha)}{4} = \sigma\left[\frac{1}{2} f T_E^4 + (1+f) T_E^4\right]$$

$$= \sigma T_E^4 \left(1 - \frac{1}{2} f\right) \Rightarrow T_E = \left[\frac{F_S(1-\alpha)}{4\sigma(1-f/2)}\right]^{1/4} = 288K = 15°C$$

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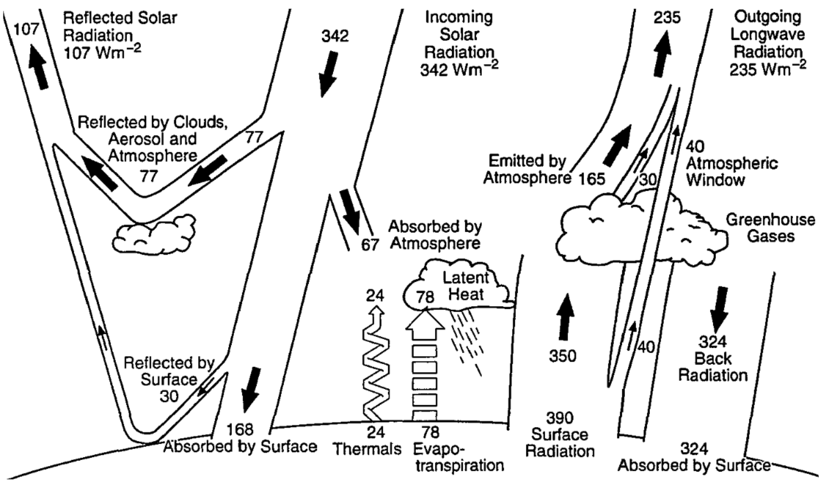
## Radiative Balance of the Earth

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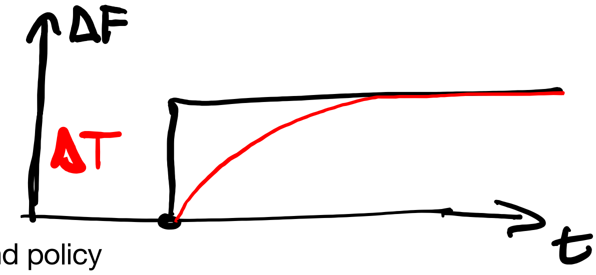
## Radiative forcing (RF) $\rightarrow \Delta F$ : $mW/m^2$

- RF measures the change as flux imbalance at TOA relative to the baseline:

$$\underset{\text{Outgoing}}{F_L} = \underbrace{(1-f)\sigma T_E^4 + f\sigma T_A^4}_{\text{balance}} - \Delta F$$

$\Delta F > 0 \Rightarrow$ warming




- It is a key measure used in climate science and policy



## Spectroscopy of Gas Molecules

- A gas molecule absorbs radiation if the energy can be used to increase the internal energy level of the molecule

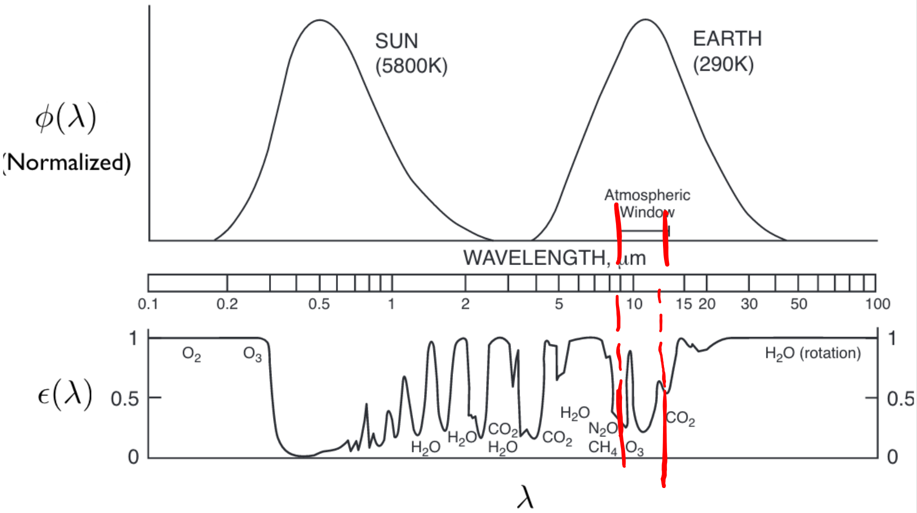
electronic state (UV)
vibrational state } IR/LW
rotational state

- Energy levels of molecules are quantized, so molecules will only absorb specific frequencies of IR

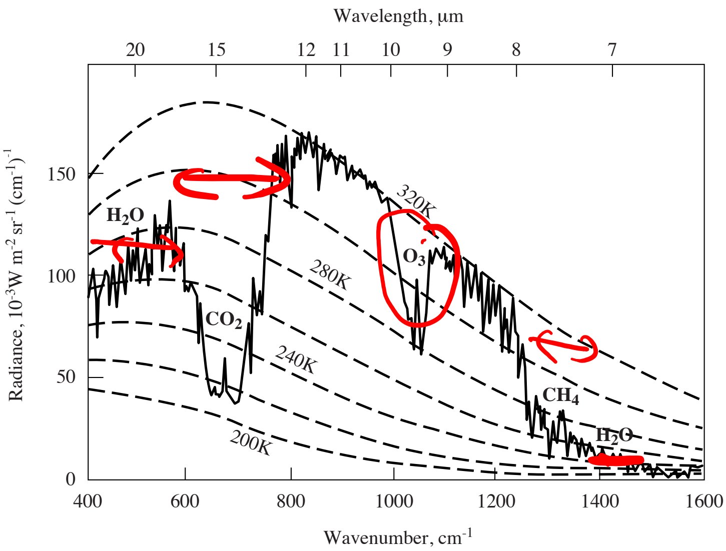
## Gas Spectroscopy and the Greenhouse Effect

Flux distribution of earth and sun, modeled as blackbodies

Absorption of radiation by the atmosphere as a function of $\lambda$




## Terrestrial radiation spectrum

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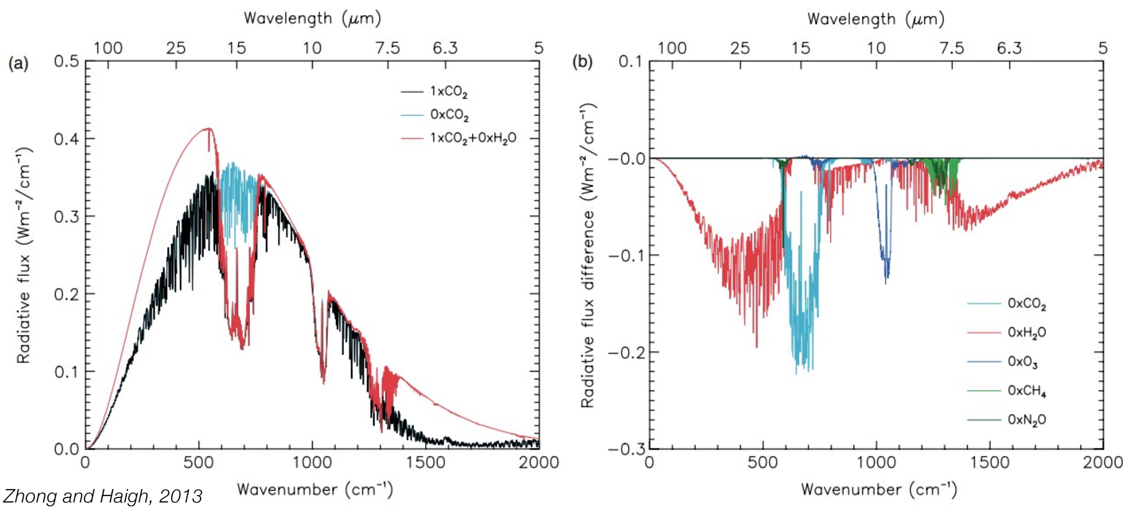
## What would this look like if we could remove the GHGs?




*Zhong and Haigh, 2013*

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## Concept question

- Which statement do you think is most likely true?
  a) The energy required to evaporate water means that water serves to damp temperature increases.
  b) Increasing temperatures increases water vapor concentrations, which serves to amplify warming.
  c) Water is in a closed cycle so there is no net impact on temperature change from water vapor.

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## Drivers of Climate Change

particulate matter (PM)

- The greenhouse effect occurs from the atmospheric concentration of naturally occurring gases and aerosols in their quasi-equilibrium concentration.
- Perturbing the atmospheric concentration will alter the radiative balance of that atmosphere leading to anthropogenic climate change.
- Consider a greenhouse gas emitted to the atmosphere. What are the factors that contribute to the magnitude of its impact on the atmosphere?

– Lifetime
– Current composition of atmos.
– Location WMGHG well mixed GHGs
– Products SLCF short lived climate forcers

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## Atmospheric Lifetimes of Greenhouse Gases

- The atmospheric lifetime of many greenhouse gases can be approximated as a simple exponential (e-folding) decay rate. Abundance from an emissions pulse is, therefore:

$$X(t) = X_0 e^{-t/\tau} \quad \text{(e-folding time)}$$

- Lifetimes are computed by modeling emission pulses to the atmosphere and calculating decay or, for stable gases, looking at radioactive decay rates. Note these are the effective lifetime of an additional unit.

| | Gas | Lifetime (Years) | Notes |
|---|---|---|---|
| Methane | $CH_4$ | 12.4 | Increases with concentration |
| | CFC-11 | 45 | |
| Nitrous oxide | $N_2O$ | 121 | Decreases with concentration |
| | $CF_4$ | 50,000 | |

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## Atmospheric Lifetime of $CO_2$

- $CO_2$ is stable in the atmosphere, but is consumed in photosynthesis and can be dissolved in water.
- The carbon exchange among the atmosphere, terrestrial biosphere and mixed ocean is is complex with many reactions occurring over "short" time-scales (months to decades).
- The carbon exchange among the terrestrial biosphere/mixed-ocean and the deep ocean and Earth's interior occur over over "long" time-scales (centuries to millennia).
- The series of all these carbon fluxes and exchanges is known as the global carbon-cycle. It can be modeled by modeling each flux with a characteristic timescale and magnitude.

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# Impulse-Response Functions for $CO_2$ Lifetime

- The carbon cycle cannot be reasonably simplified to a single decay constant.
- An impulse-response function with several independent decays can be used to model the fraction of an emission of $CO_2$ that remains in the atmosphere.

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

| $a_0$ | $a_1$ | $a_2$ | $a_3$ | $\tau_1$ | $\tau_2$ | $\tau_3$ |
|---|---|---|---|---|---|---|
| 0.2173 | 0.2240 | 0.2824 | 0.2763 | 394.4 | 36.54 | 4.304 |

- IRF is calibrated by model at a specific point; but carbon exchanges are concentration and temperature dependent.

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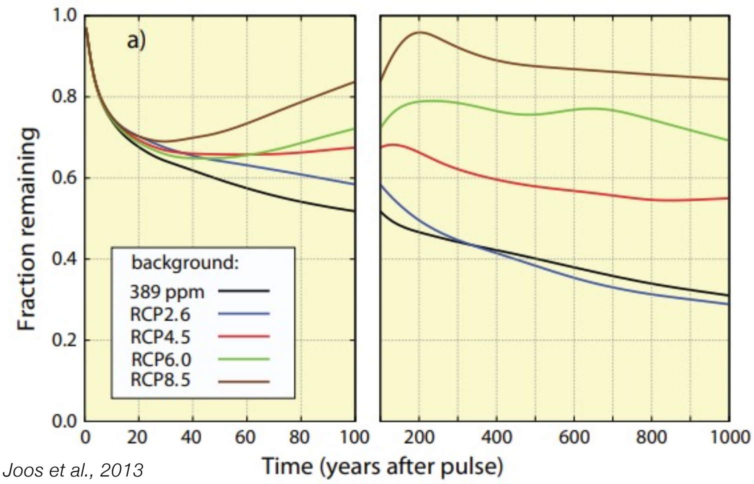
# Real IRFs from recent(ish) literature




*Joos et al., 2013*

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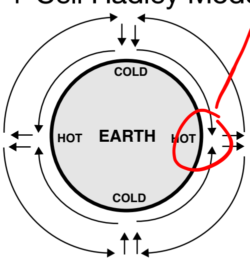
# General Circulation Primer

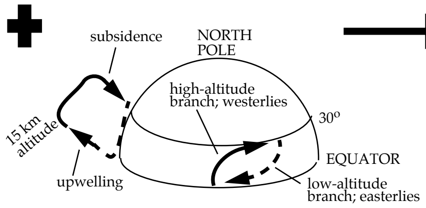
- Large–scale motions of the atmosphere are highly complex, driven by:
  - Differential solar heating of the surface of the earth resulting in pressure gradients
  - Latent heat release
  - Coriolis force

1-Cell Hadley Model

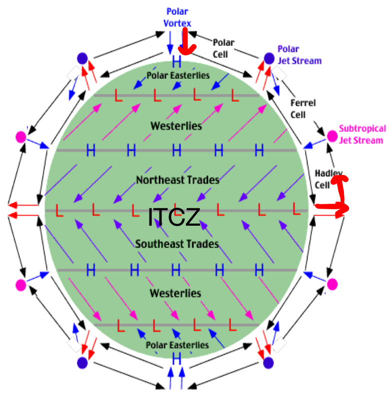
ITCZ



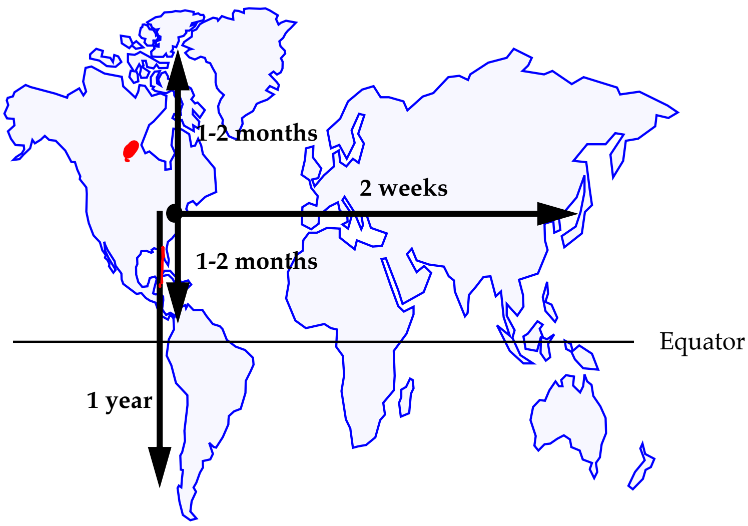

Coriolis Forces




General Circulation




# Global Horizontal Transport



## Radiative Efficiency

- Radiative efficiency is a measure of how much the net radiative balance of the earth changes for an additional unit of a greenhouse gas ($W/m^2/ppb$)
- Radiative efficiency for a well-mixed gas is primarily dependent on four factors:

1. Solar and Thermal Radiation frequencies.
2. Excitation modes
3. Concentration
4. Interactions

- Radiative efficiency is typically the most uncertain part of calculating a gas's impact on radiative balance

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## Current Radiative Efficiencies

- The estimated radiative efficiency of $CO_2$ has decreased by 30% in the last 20 years
  - 20% change from scientific understanding
  - 10% change from saturation effects
- $CH_4$ and $N_2O$ have significant spectral band overlaps, and both have had significant reductions in RE over the last 10 years.
- The radiative imbalance at a given point in time is also known as the **Radiative Forcing.**

| Gas | Radiative Efficiency $W\ m^{-2}\ ppb^{-1}$ |
|---|---|
| $CO_2$ | $1.37 \times 10^{-5}$ |
| $CH_4$ | $3.63 \times 10^{-4}$ |
| $N_2O$ | $3.00 \times 10^{-3}$ |
| CFC-11 | 0.26 |
| HG-03 | 1.76 |

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## Other Drivers of Greenhouse Effect

- Aerosols (PM)
  - Reflect (sulfates), absorb (black carbon), scatter, depends? ("brown" carbon)
- Clouds and Contrails
  - Depends on cloud properties, location, time
- The atmospheric lifetimes of clouds and aerosols are shorter than the equatorial horizontal transport times, so they are considered SLCFs (short-lived climate forcers)
  - Can still be compared to WMGHGs, but the caution must be taken to ensure that comparison is appropriate (lecture coming up).

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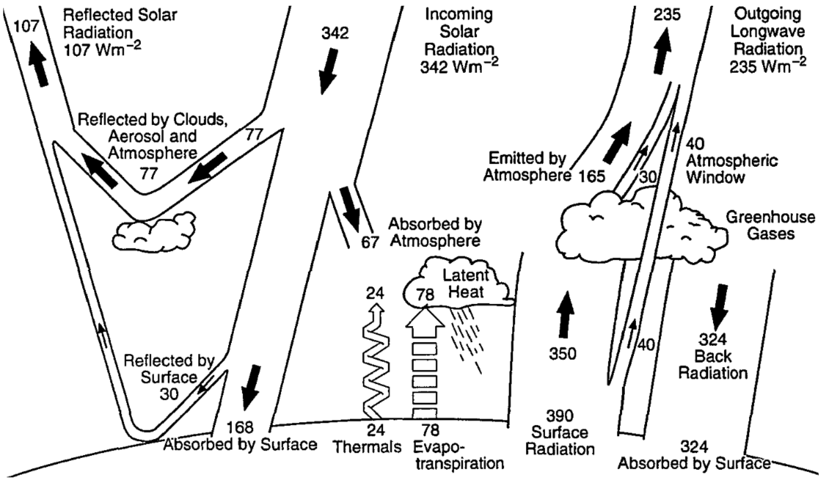
## Other Drivers of Greenhouse Effect

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## Concept question

- Which of the following are more likely to be true?
  a) Both high and low clouds are warming
  b) Both high and low clouds are cooling
  c) High clouds are warming and low clouds are cooling
  d) High clouds are cooling and low clouds are warming

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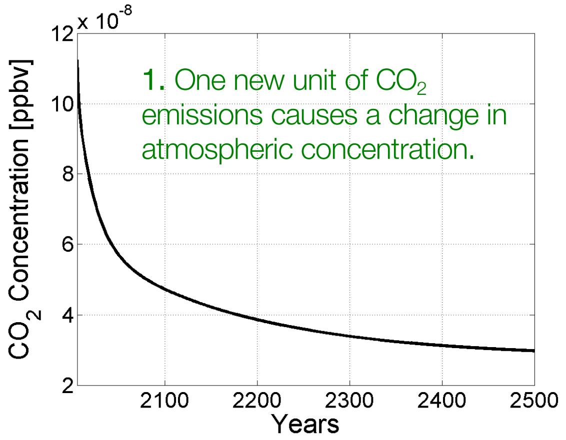
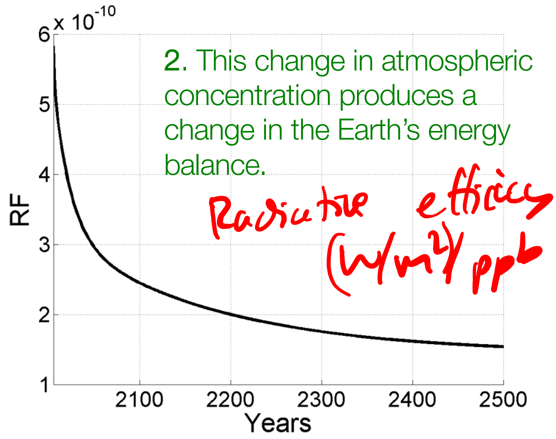
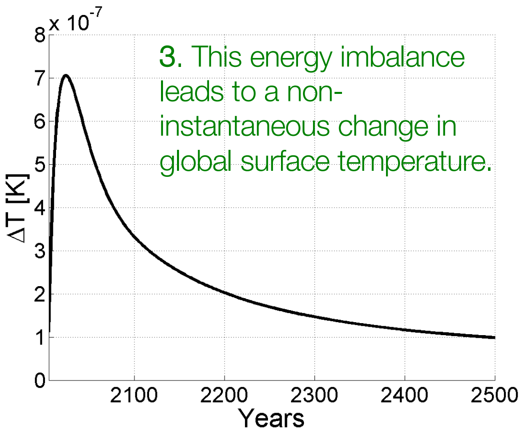
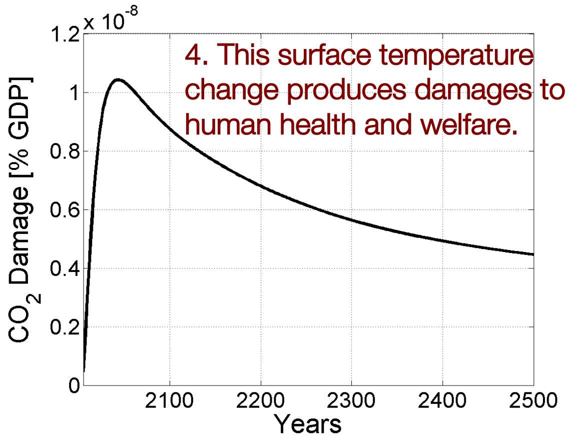
# Climate Change Emission-to-Impact Pathway [1/2]



## Climate Change Emission-to-Impact Pathway [2/2]

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## From Forcing to Temperature

- Start from the assumption that the Earth is near equilibrium:

$Q = E$    $E \propto T_s^4$

surface heating = thermal emission

- An emitted GHG immediately gives rise to a change in the radiative budget (forcing)

$$\frac{dH}{dt} = Q - E = \Delta F \text{ or } RF$$

- A change in the radiative budget gives rise to a change in temperature at the surface of the Earth (energy balance)
- But the temperature response takes time

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## From Forcing to Temperature

$$\frac{dH}{dt} = C\frac{dT_S}{dt}$$

$$C = 16.7 \pm 7 \ \frac{W\,yrs}{m^2\,K}$$

- C is the pertinent heat capacity of the Earth climate system (on the timescale of the perturbation)
- As with the carbon cycle, we can imagine the Earth's temperature response to be linked to a series of reservoirs.

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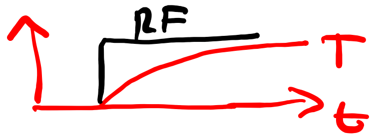
## Types of Temperature Models




- 1. Single time-scale models:

$\Delta T_s|_{100yrs} = \lambda \cdot RF$

$$C\frac{dT_s}{dt} = \Delta F - \frac{\Delta T_s}{\lambda} \quad \lambda \sim 1\frac{K}{W/m^2}$$

  - Climate sensitivity: the equilibrium temperature response given a change in radiative forcing.
  - Typically derived by modeling RF and temperature change for a doubling of $CO_2$ (1.5-4.5 K at 3.7 W/m$^2$) using a coupled atmosphere/ocean general circulation (AOGCM) climate model
- 2. AOGCMs
  - Computationally expensive
  - Cannot resolve temperature changes from small changes in emissions

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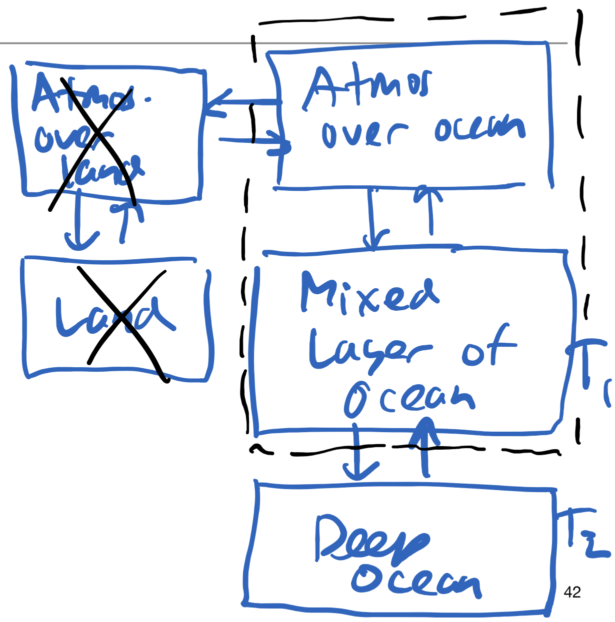
## Ocean Box Model




- Model the earth as a series of linked heat reservoirs
  - Single timescale = 1 box model
- Ocean surface currents driven by Coriolis effect, wind, continental boundaries.
- Upper ~40-100m of the ocean is relatively uniform in density (driven by turbulent mixing)
- Deep ocean is the largest "heat sink" by mass, but is effectively cut-off from the dynamic climate system… for short time periods.

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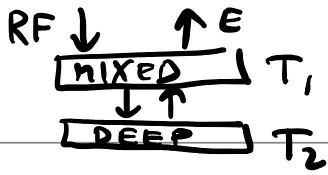
## Ocean Box Model 2 Box-Ocean




- Assuming a 2-Box Ocean, temperature can be modeled assuming heat exchange between the mixed layer and the deep ocean.

$$C_1 \frac{dT_1}{dt} = \Delta F - \frac{T_1}{\lambda} - K_M (T_1 - T_2)$$

Mixed Layer

$$C_2 \frac{dT_2}{dt} = K_M (T_1 - T_2)$$

Deep Ocean

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## Efficacy

- Depending on temporal, altitudinal, spatial, and other heterogeneities, similar RFs may lead to different expected temperature changes.

$$\Delta T_s = \lambda_{CO_2} \cdot r$$

- Thus – using an "efficacy" (lambda or r) can convert a RF to an "effective RF", accounting for how likely the RF from that species is to create the same amount of temperature change compared to the same RF from $CO_2$.

- Ex. Ozone in the upper troposphere has an efficacy of ~1.05, contrails may have an efficacy as low as 0.5 or as high as 1.1.

- The efficacy concept is controversial and highly uncertain; attempts to redefine Radiative Forcing to negate the need for efficacies.

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## Economics of Climate Change

***The economics of climate change have the least certainty but the greatest importance to policy makers***

- Impacts cover a broad range including health, safety, land use, food, economic production
- Time scales for impacts can be decadal
- Some impacts difficult to monetize.
  - What is the cost of lowered food production?
  - What is the cost of species loss?
  - What is the cost of infant mortality?

Heat
Humans
Natural Env.
Agriculture /forests
Disease vectors
Sea level rise
Weather
Low p. /high impact events

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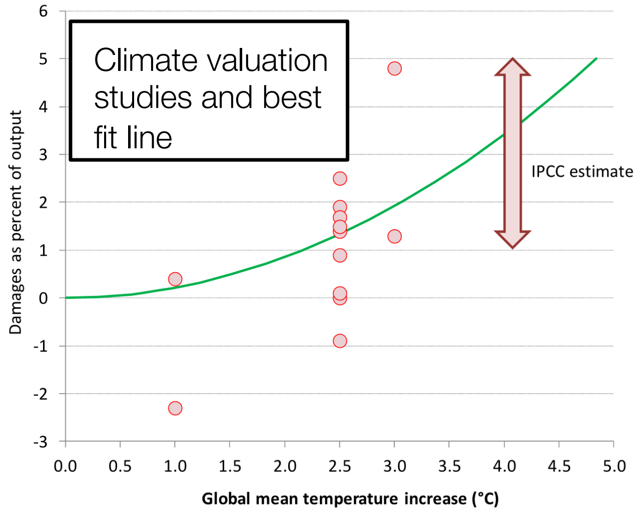
## Valuation Studies

- Most (but not all!) studies predict warming leading to significant net negative impacts.
- Sample Damage Function (DICE):

$$D = a(\Delta T)^2$$

↑% of GDP ↑K




Tol 2009, Nordhaus 2013

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