

GE510 Physical Principles of the Eenvt

Radiative Forcing of Climate

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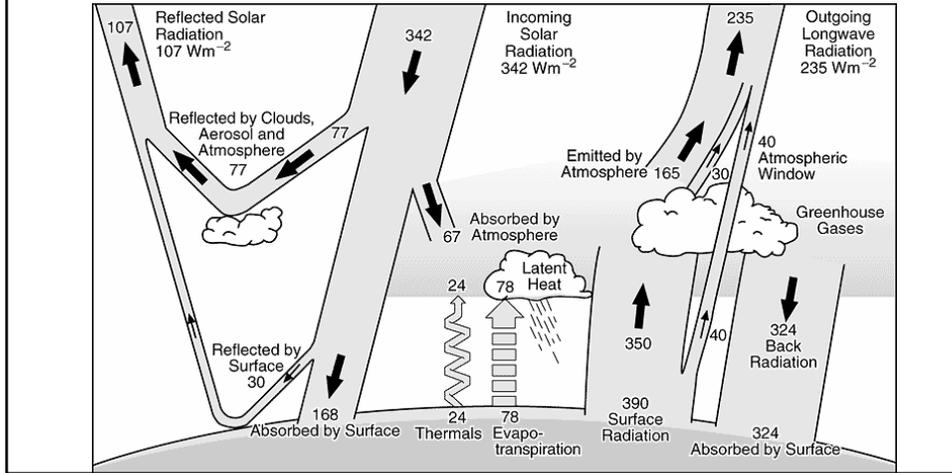
- 1. What is radiative forcing of climate? – Conceptually**
 - A simple definition
 - Physical properties of molecules that make them GHG
 - A simple greenhouse effect model

- 1. What is radiative forcing of climate? – Operationally**
 - IPCC definition and use
- 2. Strengths and Limitations of the concept**
- 3. Specific forcings by GHG and aerosols.**

Radiative Forcing of Climate

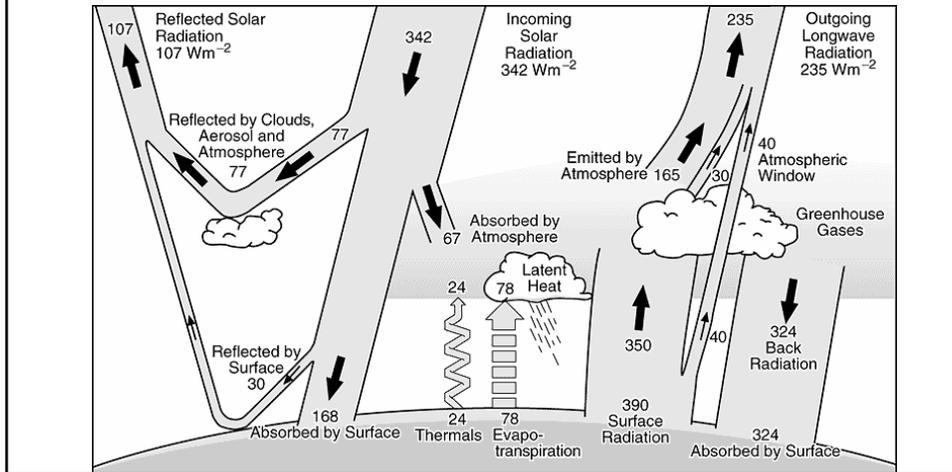
Simple Definition:

“ A change in the input or output of radiation to/from the climate”



Radiative forcing could be due to a change in the solar input, or outgoing radiation, or both.

After imposition of this change, over time a new energy balance would result, characterized by surface and atmospheric temperatures



- **Units of radiative forcing: W/m²**
- **“+” radiative forcing – warms planet**
- **“-” radiative forcing – cools planet**

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Physical properties of molecules that make them GHG

Observations:

Diatomic molecules and atoms are not usually good infrared absorbers

Tri-atomic and higher molecules usually are. Why?

Short answer: more complex molecules have a greater repertoire of available places to store and release energy.

This is ultimately based on quantum mechanics – atoms and molecules can only accept or deliver photons in discrete energy levels.

Physical properties of molecules that make them GHG

Analogy to vending/change machines (Philander):
Lower dollar amounts correspond to lower energy photons

O₂ only takes and gives \$10, \$20 bills

CH₄ takes/gives \$5, \$1, 50 cent coins

CO₂ takes/gives \$1, 50, 10, 5, 1 cent coins



Thermal wavelengths are weak and only perturb the lowest available energy slots in tri-atomic molecules. These are rotational and vibrational energy states.

Diatomic molecules don't have these weak modes to perturb

Visible light/UV/x-rays don't bother with these weak absorption modes.

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CHAPTER 19 MOLECULAR ORBITALS AND SPECTROSCOPY

Table 19-3
Spectroscopic Experiments

Spectral Region	Frequency (s^{-1})	Energy Levels Involved
Radio waves	10^7 - 10^9	Nuclear spin states
Microwave, far infrared	10^8 - 10^{12}	Rotational
Near infrared	10^{12} - 10^{14}	Vibrational
Visible, ultraviolet	10^{14} - 10^{17}	Valence electrons
X-ray	10^{17} - 10^{19}	Core electrons

Molecular Energy Levels

The excited states of atoms arise from the promotion of an electron of an atom into orbitals of higher energy. Excited electronic states in molecules are similarly, and can be described in the framework of the molecular-orbital theory that has been developed so far. In addition to the excited electronic states, the motion of the nuclei must be considered. This was not a factor with atoms, which have only one nucleus. The additional modes of motion that are possible in molecules mean that they have many more allowed energy levels than do atoms. The absorptions and emissions of electromagnetic radiation that accompany transitions between these levels form patterns that are quite complex, even in small molecules. In this section, we outline the effects of radiation of various frequencies on molecules in causing changes of energy level. The results are summarized in Table 19-3.

Let us begin with the highest-energy photons, those called gamma rays and x-rays. These photons carry enough energy to excite core electrons out of their stable orbitals close to the nuclei up to high-energy outer orbitals, or to remove the core electrons from the molecule altogether via photoemission. Careful studies of the way absorption in the x-ray region depends on wavelength have established patterns that depend on the environment as well as the identity of the absorbing atom; x-ray absorption thus provides information about both.

Light in the ultraviolet and visible region of the spectrum carries somewhat less energy (typically 50 to 500 $kJ\ mol^{-1}$) and cannot unseat the tightly bound

Molecules can spin, flex, bend, and stretch, in motions that are possible only because they have two or more centers of mass.

Figure 19-14 The three types of vibrational motion possible for a bent triatomic molecule. The displacements of each atom during each type of vibration are shown by arrows.

Relation of thermal radiation absorption to higher energy radiation absorption

Think of the GHG we've discussed so far:

CO₂, CH₄, N₂O, CH₄, O₃, CFC

All tri-atomic or larger.

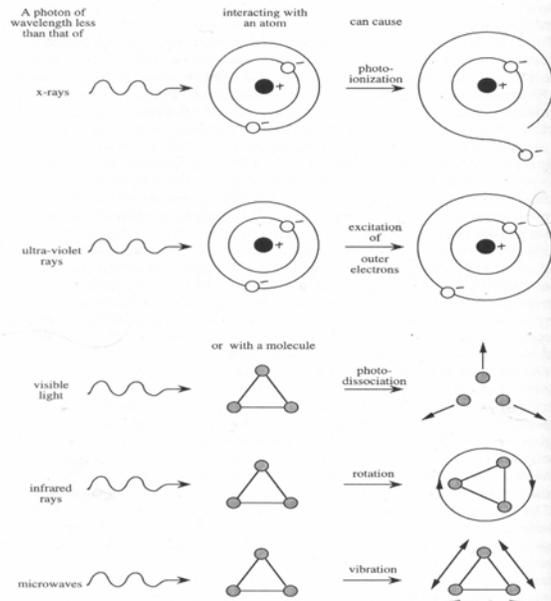


Figure 3.7 Possible interactions between a photon and atom or molecule. The most energetic photons (with the shortest wavelength) are at the top of the figure; toward the bottom, energy levels decrease, and wavelengths increase.

Taking stock II:

We've now discussed thermal properties of the atmosphere and earth's surface, why certain molecules are good greenhouse absorbers.

Now let's consider a simple energy balance that quantitatively demonstrates the greenhouse effect.

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1. What is radiative forcing of climate? – Conceptually
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- A. Glass represents the ‘normal’ greenhouse effect on earth and is at top of atmosphere
- B. Solar shortwave radiation S largely makes it to surface
- C. For energy balance, top of glass must send S back out.
- D. Greenhouse gases don’t have a preferred direction; they send S units in both directions – up and down.
- E. Thus, the surface of the earth receives $2S$ due to the greenhouse effect – instead of $1S$ if there were no atmosphere!

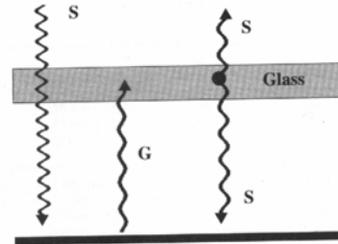


Figure A3.3 An idealization of the greenhouse effect in which the greenhouse glass is entirely transparent to sunlight, of intensity S , from above, and is entirely opaque to infrared heat, of intensity G , from the surface below. In a state of equilibrium the glass attains a temperature which is such that it radiates S units from each of its surfaces.

G = thermal radiation emitted from earth = $2S$

Stefan-Boltzmann:

$$2S = \epsilon\sigma T^4 \rightarrow T = (2S / \epsilon\sigma)^{1/4}$$

With greenhouse effect, versus

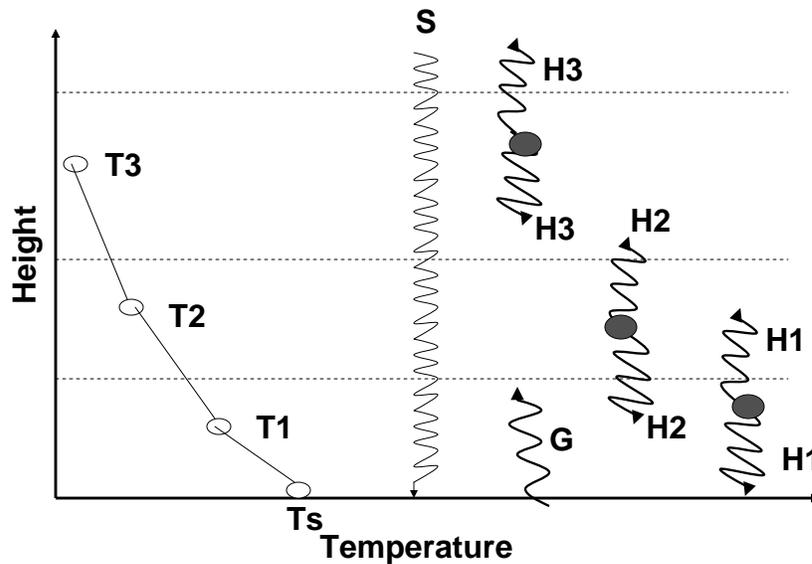
$$S = \epsilon\sigma T^4 \rightarrow T = (S / \epsilon\sigma)^{1/4}$$

Without greenhouse effect.

We have demonstrated how the 'natural' greenhouse effect (e.g. H₂O, natural CO₂) elevated surface temperature.

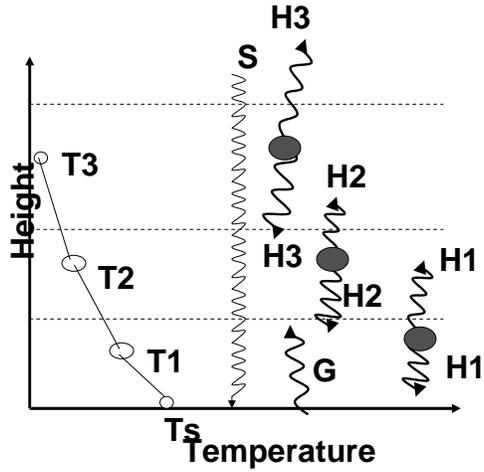
Next time we will extend this simple model to show how the addition of greenhouse gases increases surface temperature.

More realistic: multiple layers represent vertical distribution of atmospheric gases, including GHGs



Energy Balance:

1. Out of top: $H_3 = S$
2. Third layer: $H_2 = 2H_3$; thus $H_2 = 2S$
3. 2nd layer: $H_1 + H_3 = 2H_2$
Thus $H_1 = 3S$
3. Ground: $S + H_1 = G$
Thus $G = 4S$



Solving for temperatures:

$$T_s = (4S/\epsilon\sigma)^{1/4}$$

$$T_1 = (3S/\epsilon\sigma)^{1/4}$$

$$T_2 = (2S/\epsilon\sigma)^{1/4}$$

$$T_3 = (1S/\epsilon\sigma)^{1/4}$$

Thus, temperatures decrease with height.

We can generalize to any strength of greenhouse effect by using optical depth:

$$\epsilon\sigma T^4 = (1 + \text{Optical Depth}) \times S$$

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Radiative Forcing (IPCC):

“The radiative forcing of the surface-troposphere system due to the perturbation in or the introduction of an agent is the change in net irradiance at the tropopause AFTER allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values.”

-A mouthful!

-Let’s try to deconstruct this...

“The radiative forcing *of the surface-troposphere system* due to the perturbation in or the introduction of an agent is the change in net irradiance at the tropopause AFTER allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values.”

Why surface-troposphere system?

“The tropopause is chosen because... in a global and annual mean sense... they are so closely coupled that they behave as a single thermodynamic system” – IPCC 1994

Stratosphere: response time of months to climate forcing disturbances

Surface/Troposphere: response time of years/decade to climate forcing disturbances – due largely to ocean response

“The radiative forcing of the surface-troposphere system due to the perturbation in or the introduction of an agent is the change in net irradiance at the tropopause *AFTER allowing for stratospheric temperatures to readjust to radiative equilibrium*, but with surface and tropospheric temperatures and state held fixed at the unperturbed values.”

What is ‘readjustment’ of the stratosphere?

-Let’s use an example: doubling CO₂ in the troposphere reduces outgoing infrared radiation and thus constitutes a positive radiative forcing on the troposphere/surface system.

-As stated earlier, it would take a decade for the troposphere/surface to RESPOND to this forcing and restore balance by increasing temperature, but only a few months by the stratosphere to decrease temperature.

-To restore an earth energy balance, stratospheric temperatures must cool if troposphere/surface temperatures warm. If not there would be a net increase in total energy leaving earth to outer space with a greenhouse effect.

“The radiative forcing of the surface-troposphere system due to the perturbation in or the introduction of an agent is the change in net irradiance at the tropopause *AFTER allowing for stratospheric temperatures to readjust to radiative equilibrium*, but with surface and tropospheric temperatures and state held fixed at the unperturbed values.”

What is ‘readjustment’ of the stratosphere?

-In essence, this definition of radiative forcing puts the stratosphere ‘in whack’ (that is, in equilibrium) with the radiative effects of a perturbing agent, while allowing the region of interest (troposphere/surface) to remain ‘out of whack’.

-This is very artificial! It is a “modeling concept” (IPCC 2001 p. 353) – I would say even a ‘modeling construct’.

-It doesn’t correspond to a real scenario but is better thought of as a quantitative measure of potential for climate change.

-So if so artificial, why define it this way???

“The radiative forcing of the surface-troposphere system due to the perturbation in or the introduction of an agent is the change in net irradiance at the tropopause *AFTER allowing for stratospheric temperatures to readjust to radiative equilibrium*, but with surface and tropospheric temperatures and state held fixed at the unperturbed values.”

Why allow ‘readjustment’ of the stratosphere?

-It turns out that defining radiation forcing in this way leads to a much more general correlation between forcing agents and climate (temperature) response.

