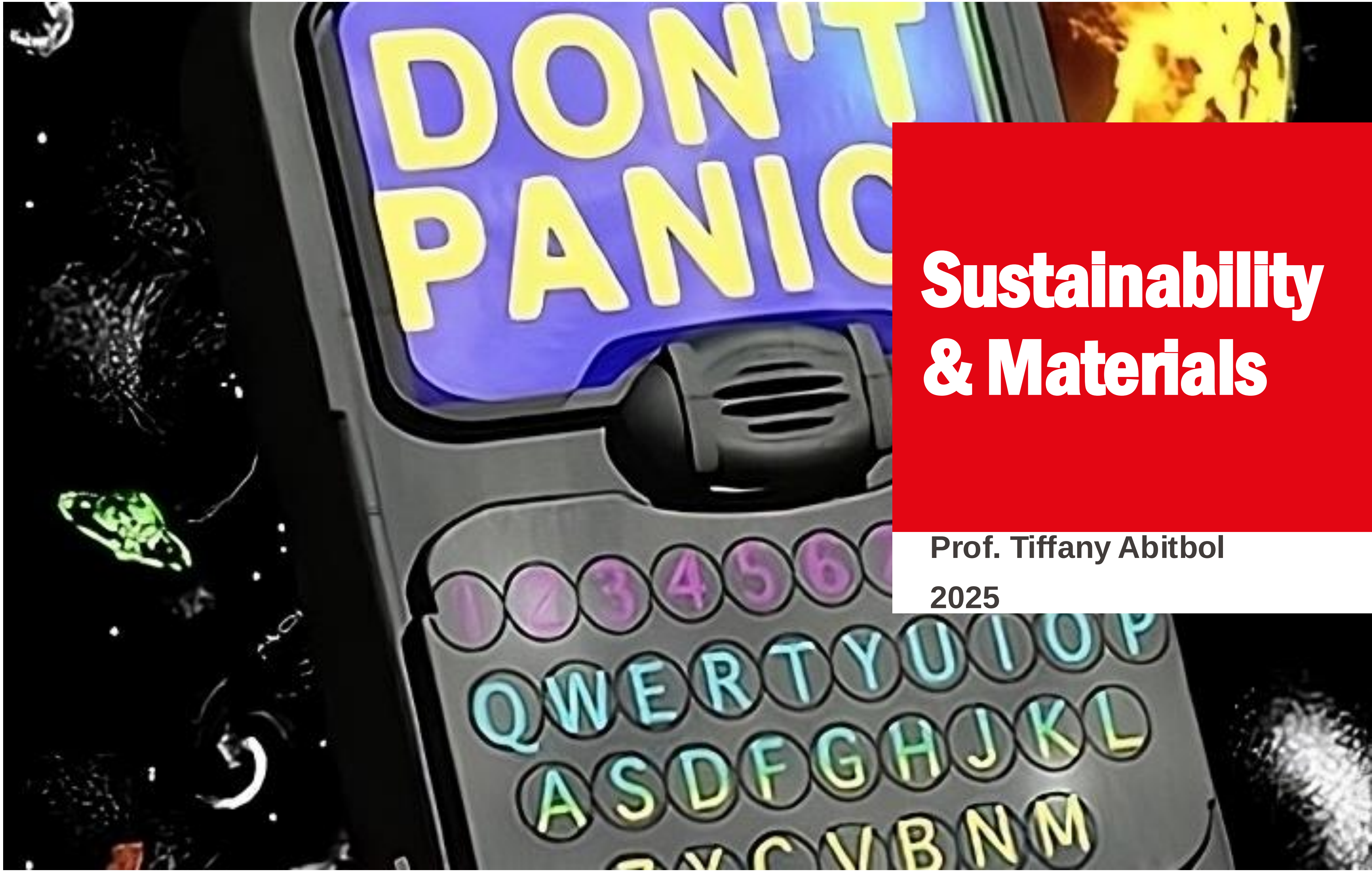


Sustainability & Materials

Prof. Tiffany Abitbol

2025

Assignment – “clickbait”

- Recall: 1 assignment, 2/6 points, individual work

- What’s it all about? Our social media is inundated with sustainability topics - from the terrifying to the uplifting.

- Pick a post/a video/whatever format of content, tell me about why it resonated with you, and ***most importantly follow the scientific thread like a detective.***

- Find the scientific source(s) that the article was based on. Provide the citation(s). What is actualized described in the ***scientific literature***? Is the post sensationalized click-bait or accurate? Or a bit of both? Break it down for me, deconvolute the topic!

- If you don't do social media, congrats! Borrow from a friend for the purpose of this assignment.

clickbait
It means what you think it means: bait for clicks. It's a link which entices you to click on it.

-Urban dictionary

Assignment – “clickbait”

- When are you supposed to work on this? During exercises and at home. If you want feedback and help, please ask.
- When is it due? By Friday Mar 22 at 17.
- **The assignment description is on this week’s Moodle** (Feb 26 Moodle), this is also the week where you submit/return the assignment (please make a note for yourself!)
- 10-15 pages, less is more but be thorough, with detailed refs, etc.,
- I’ll tell you more about the group project (presentations in last 2 weeks of class) in the coming weeks

clickbait
It means what you think it means: bait for clicks. It's a link which entices you to click on it.

-Urban dictionary

A non-comprehensive timeline of sustainability

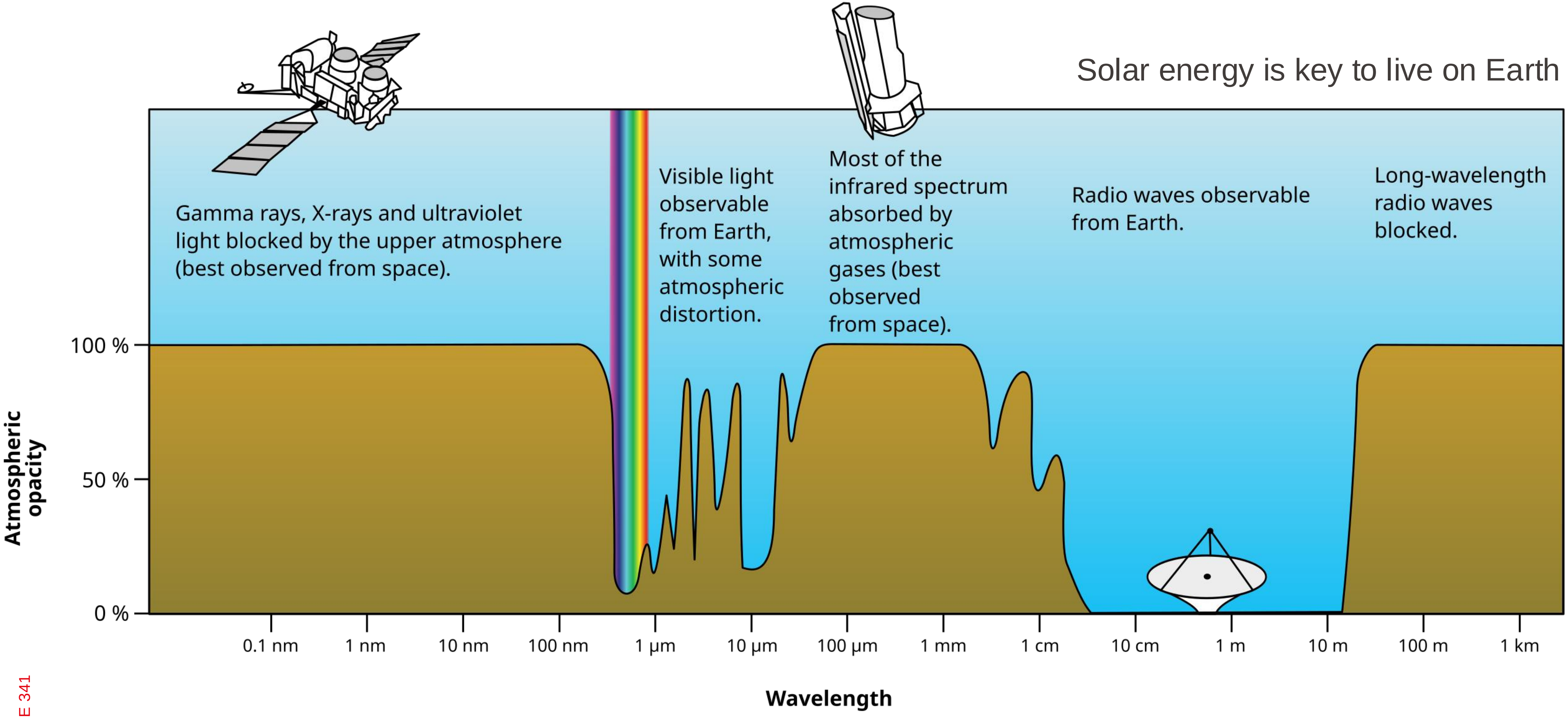
- The Silent Spring by Rachel Carson, 1962
- Earth Day, 1970
- Greenpeace, 1971
- **Phase out of CFCs (1980s) – *Montreal Protocol***
- “Our common future” by the UN Brundtland Commission (1987)
- **Green chemistry (1990s)**
- **Carbon as a currency – *Kyoto Protocol (early 2000s)***
- **Climate change (1.5 °C) – *Paris Agreement (2010s)***
- **Roadmap for prosperity – *UN Sustainable Development Goals (2010s)***

FILE - In this April 23, 1970, file photo, part of crowd observing Earth Day, including, youngster wearing "Let Me Grow Up:" sign on back relaxes on hilltop in Philadelphia's Fairmount Park in Philadelphia. (AP Photo)

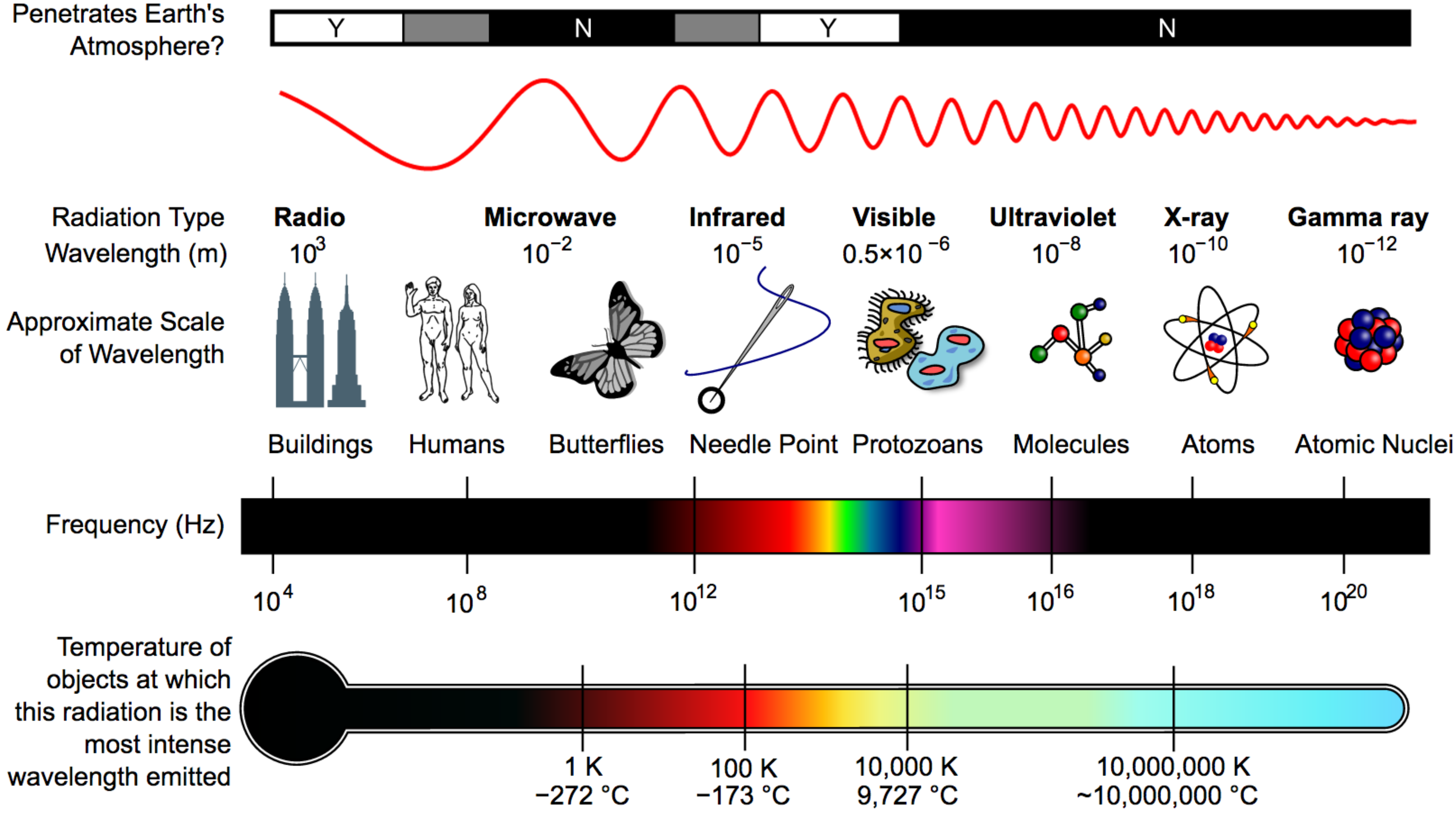
Silent spring summary
Earth Day
Brundtland Report

The electromagnetic spectrum

Solar energy is key to live on Earth



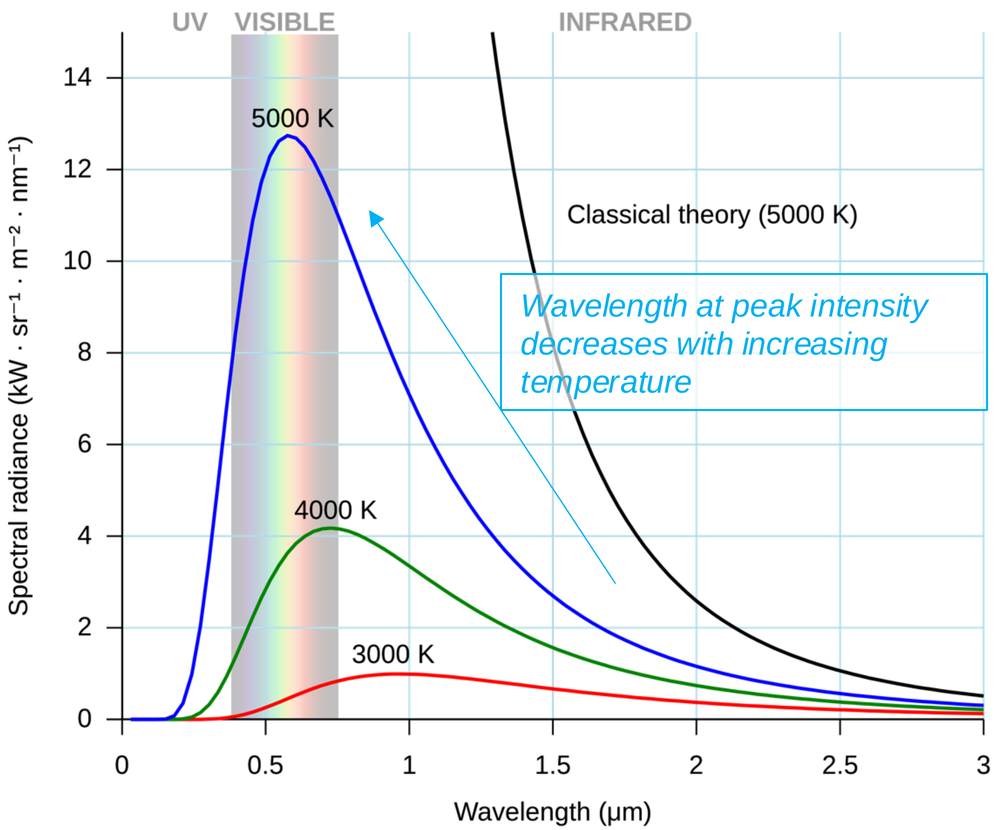
Electromagnetic spectrum



Electromagnetic spectrum

Blackbody radiation

Emission of blackbodies at different temperatures:



- A blackbody is an idealized object that absorbs and emits all EM radiation (no reflection or transmission)
- Perfect absorber & perfect emitter
- Intensity and spectral distribution of the emission ***depends only on the temperature*** of the body
- The sun, the earth, humans can be approximated as blackbodies
- At room temperature (RT) most objects emit IR, as temperature increases, emission can go into the visible and beyond (hot objects look red…)

[Blackbody radiation](#)
[Blackbody](#)

Wien's law

- Wien's law describes the relationship of the wavelength at peak intensity and temperature in Kelvin

$\lambda_{peak} = b/T$

$b \approx 0.0029$ m K

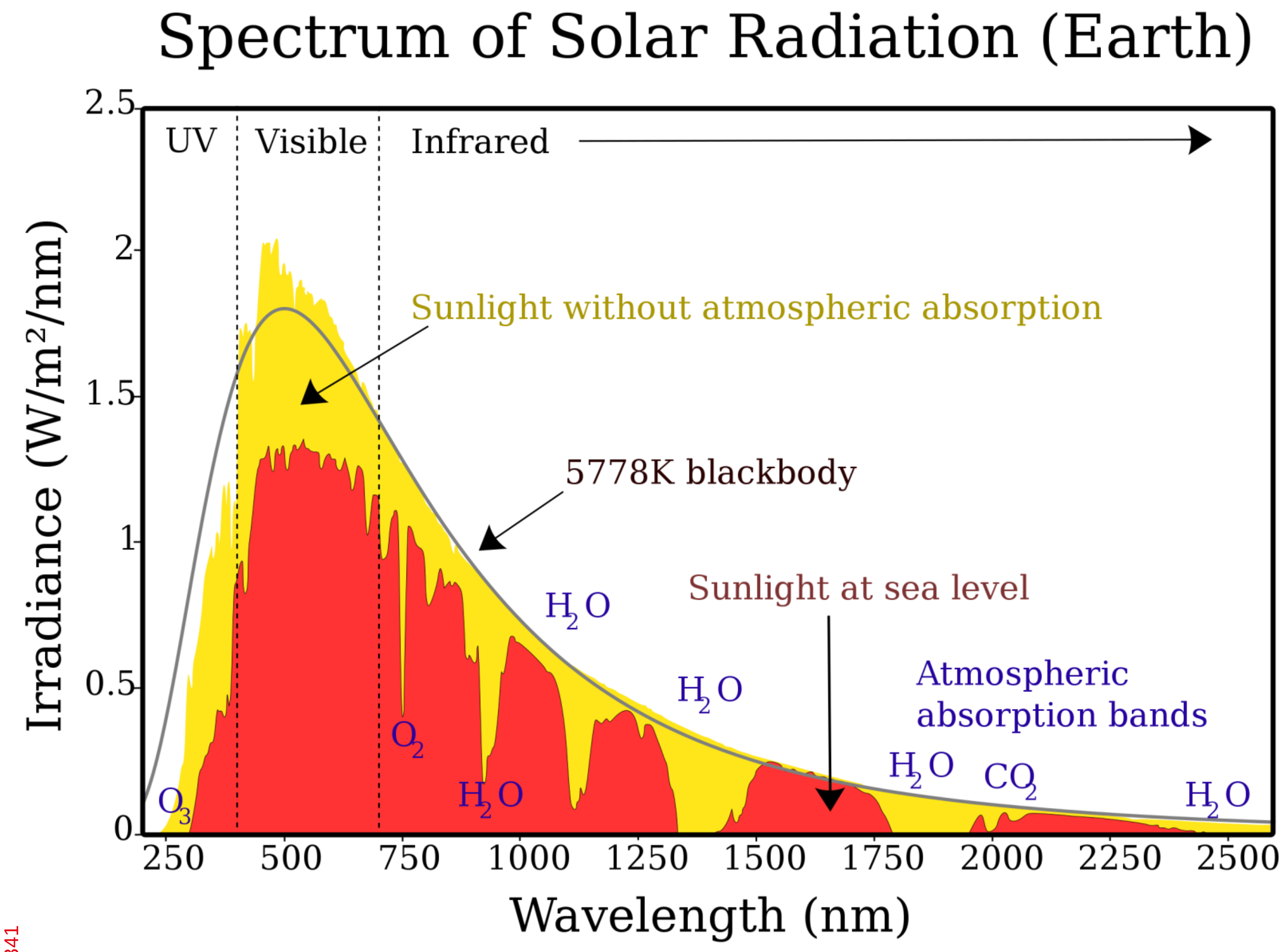
If we consider a human at 32 °C:

$\lambda_{peak} = b/305\ K = 9.05\ \mu m$

Thermal camera range = 7-14 μm

- You can use this to estimate the wavelength at peak intensity for different blackbodies

Blackbody radiation
Blackbody

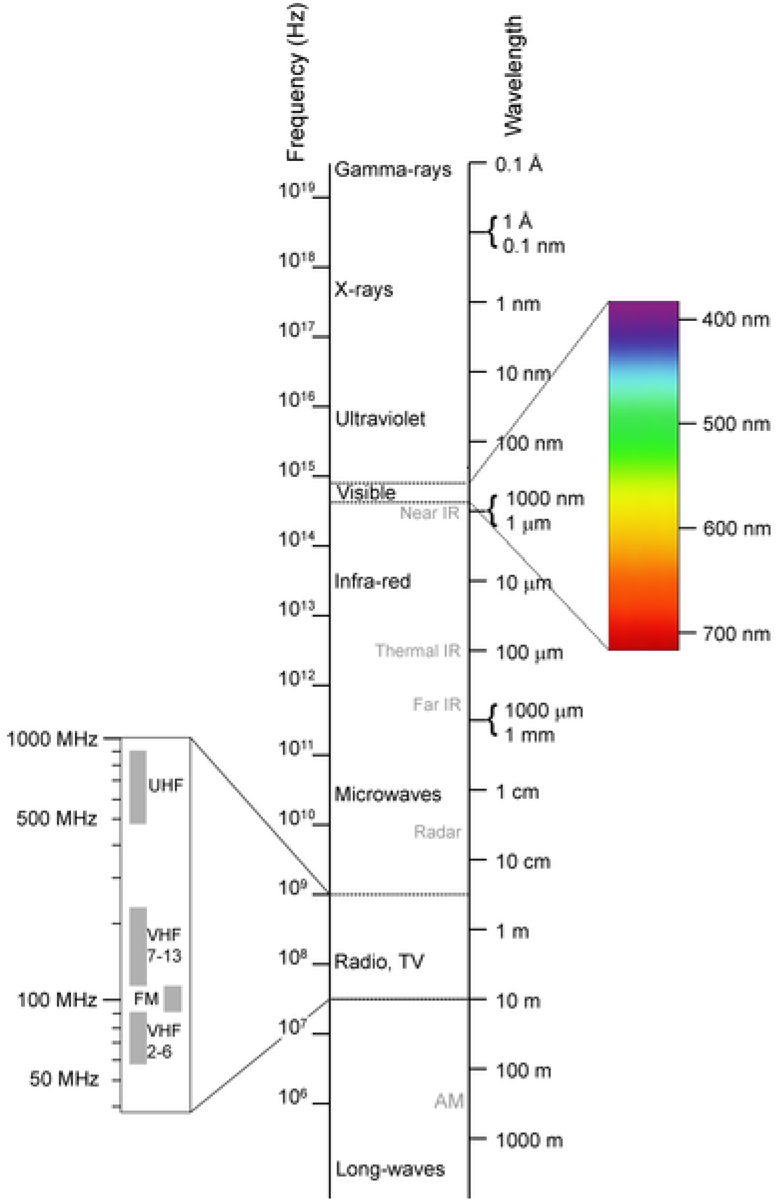


- The sun as a black body
- Radiation from sun to earth, through the atmosphere
- Surface irradiance is lower than at top of atmosphere due to light scattering and absorption by atmospheric gases
- Earth receives mostly 300-2500 nm
- Solar radiation is mainly visible and NIR (0.76-1 µm)
- Ozone! The Earth's Sunscreen
- GHGs! The Earth's Blanket (later)

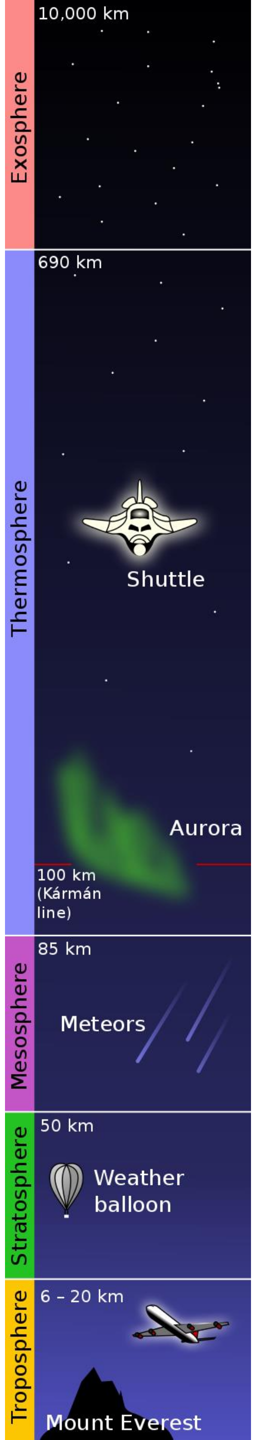
Solar radiation

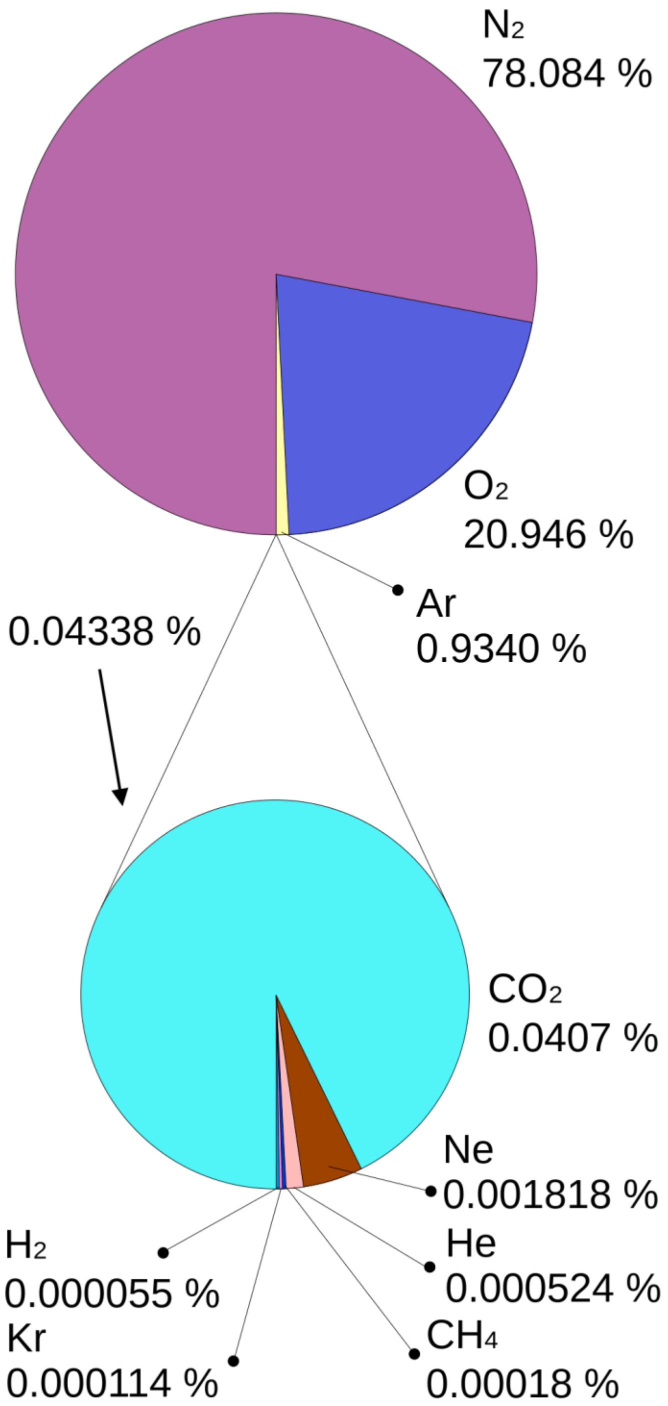
Breaking down the solar spectrum

- Sunlight spectrum is mostly 100 nm – 1 mm wavelength range, consisting of:
  - **UVC**: 100-280 nm; mostly absorbed by the atmosphere with very little reaching the earth; highest energy, most damaging
  - **UVB**: 280-315 nm; also significantly absorbed in the atmosphere, together with UVC responsible for ozone generating chemistry, directly damages DNA and causes sun burns (aging, cancer)
  - **UVA**: 315-400 nm; tanning booth UV but also damages DNA
  - **Visible**: 380-800 nm; strongest output range of solar radiation, visible by eye; photosynthesis!
  - **Infrared** (IR): 700 nm - 1 mm; the sun mainly emits near IR (< 1 µm wavelength); some absorbed and re-emitted by GHGs
- The atmosphere has a key role in filtering out harmful UV radiation (Thank you ozone!), while allowing life-sustaining visible light to reach the earth (photosynthesis)



EM radiation





What's the atmosphere made of?

- Dry composition
- Mostly O_2 and N_2; transparent to IR (not GHGs)
- Trace gases, including CO_2 that absorb and emit IR (same as other GHGs)
- Ozone is predominately found in the **stratosphere**, with an abundance that depends on altitude (average concentration in atmosphere is about 0.3 ppm = 0.00003%)

Earth's atmosphere

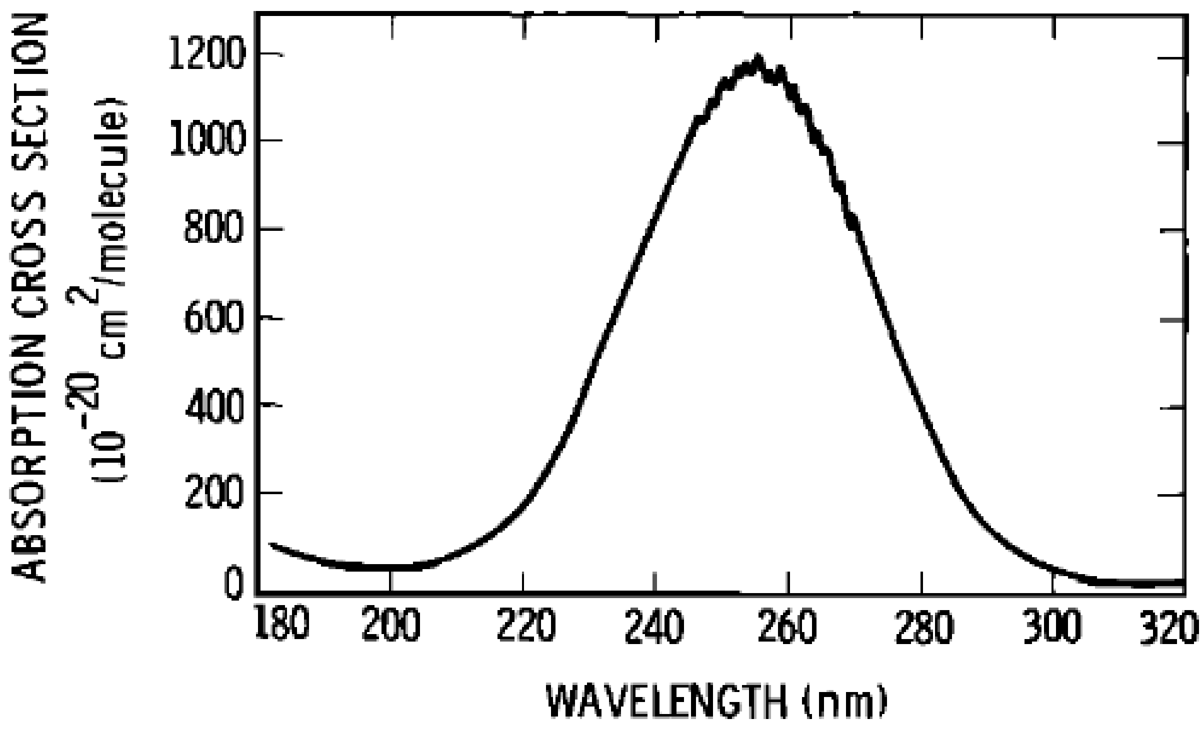
Table 1. Proposed planetary boundaries.

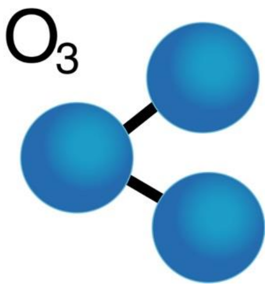
Earth System process	Control variable	Threshold avoided or influenced by slow variable	Planetary Boundary (zone of uncertainty)	State of knowledge*
Stratospheric ozone depletion	Stratospheric O_3 concentration, DU	Severe and irreversible UV-B radiation effects on human health and ecosystems.	<5% reduction from pre-industrial level of 290 DU (5%–10%)	1. Ample scientific evidence. 2. Threshold well established. 3. Boundary position implicitly agreed and respected.

- 1 DU is equivalent to a layer of pure ozone that is 0.01 mm thick at standard temperature and pressure (temperature = 0°C, pressure = 1 bar)
- Average ozone in the atmosphere is about 300 DU, equivalent to a 3 mm layer at standard conditions (2 pennies)
- A "hole" is where the concentration is around 100 DU; not an actual hole

Ecology and Society 14(2): 32
http://www.ecologyandsociety.org/vol14/iss2/art32/

Ozone UV absorption





- UV absorption spectra for ozone at 298 K
- Peak absorption is around 254 nm, which is UVC
- The absorption of UV drives its production/destruction cycles in the atmosphere

Ozone absorption cross-sections_1986

Ozone cycle (natural cycle)

FORMATION

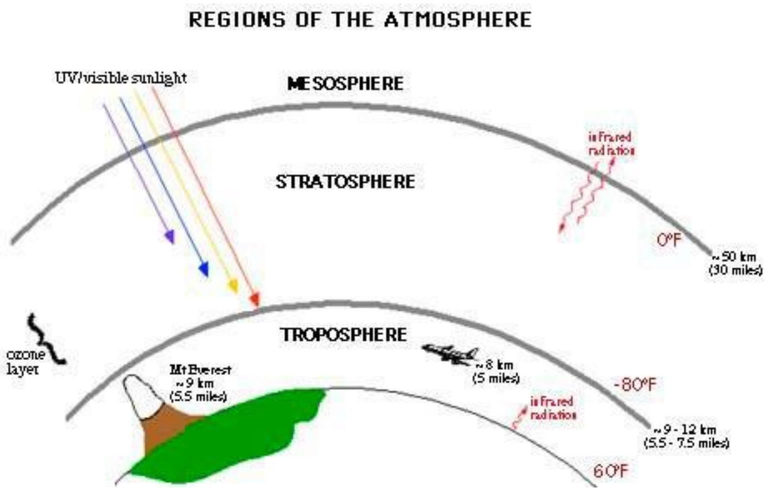
$$O_2 \xrightarrow{\lambda < 200nm} O + O$$

$$O + O_2 \rightarrow O_3$$

DESTRUCTION

$$O_3 \xrightarrow{200 < \lambda < 300nm} O_2 + O$$

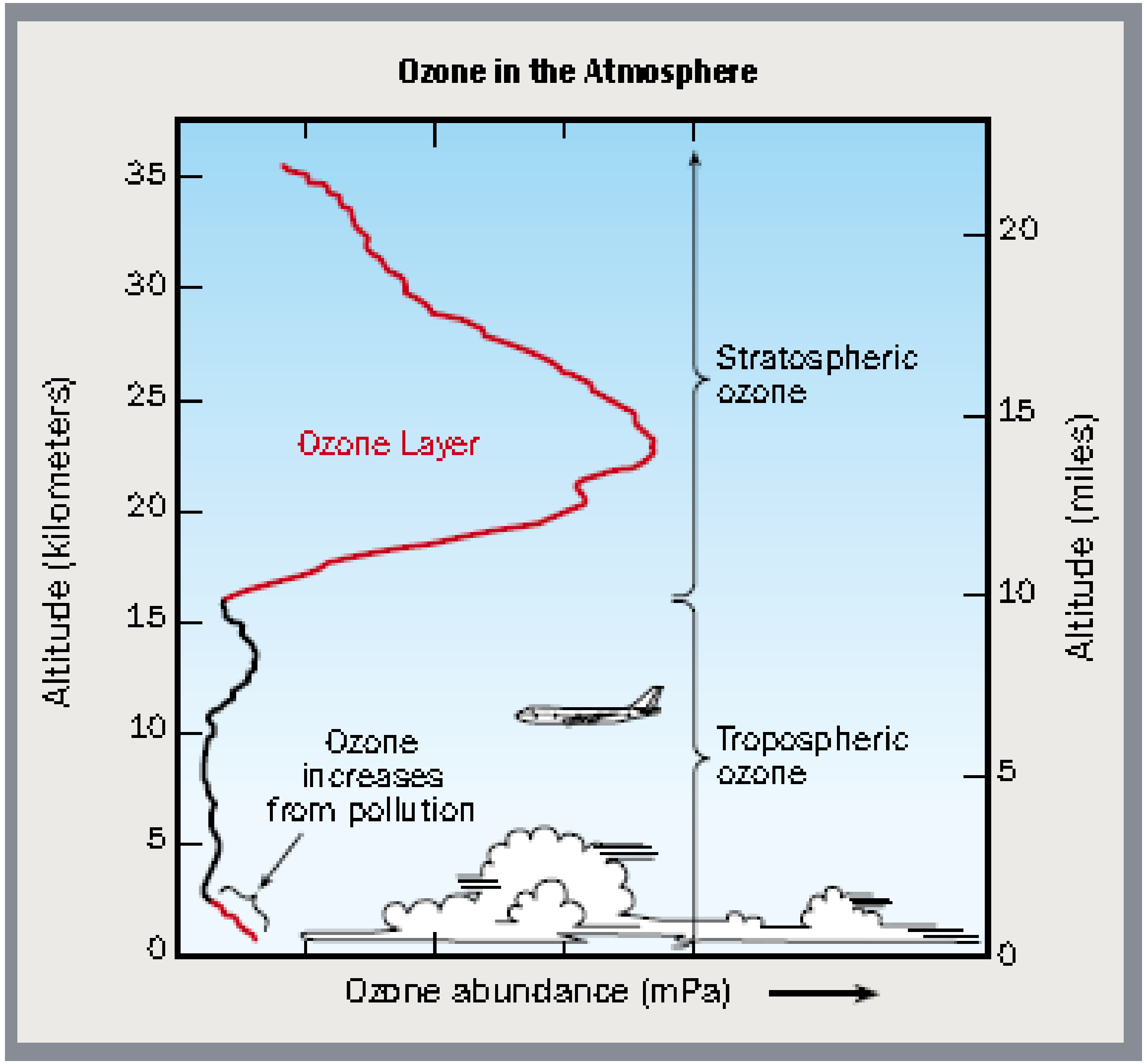
$$O + O_3 \rightarrow O_2 + O_2$$



- Oxygen constantly input into atmosphere through photosynthesis, which means that ozone can regenerate
- Ozone and oxygen are continuously interconverted in this cycle
- Called the **Chapman Cycle**

Ozone depletion

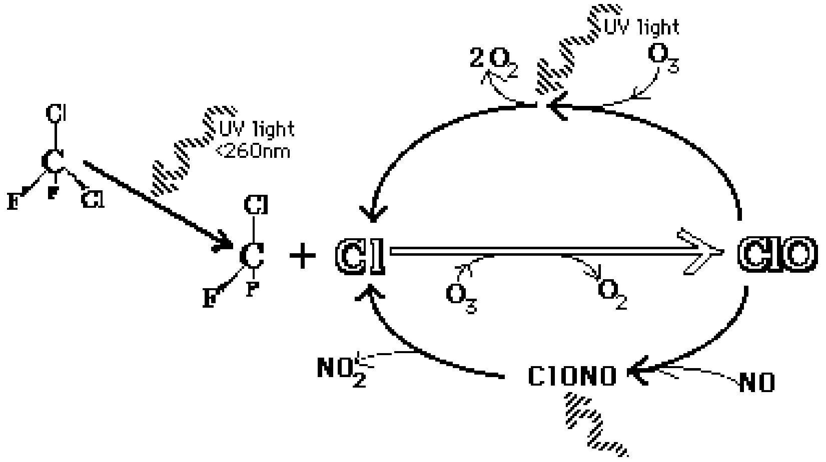
- Stratospheric ozone layer located at altitude between 10-40 km
- O_3 layer in stratosphere protects earth from harmful UV radiation (200-315 nm)
- Concentration of ozone in stratosphere varies seasonally and by altitude (see figure at left)
- In the 1970s, scientific evidence for ozone depletion *beyond normal cycles*
- "Hole" in ozone layer was first noticed over Antarctica in the 1980s (1985 Nature paper)



Nature paper
https://ozone.unep.org/ozone-and-you
https://www.epa.gov/ozone-layer-protection/basic-ozone-layer-science
https://www.nas.nasa.gov/About/Education/Ozone/chemistry.html

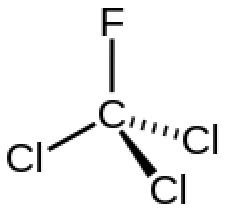
Ozone depletion

- **Ozone depleting substances** (ODS); *Hint – Novel entities!*
- Chlorofluorocarbons (CFCs) used as aerosol propellants, blowing agents for foams and packing materials, flame retardants, refrigerants, etc.,
- CFCs contain chlorine, fluorine, bromine, and carbon atoms and are ***extremely stable***
- The high stability of these molecules are why they make it up to the stratosphere (most molecules degrade in the troposphere)
- In the stratosphere, they react with high energy UV light, which can break their bonds, releasing halogens
- Halogens (e.g., F, Cl, Br) catalyze ozone degradation

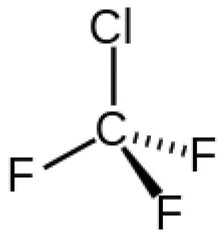


Ozone chemistry

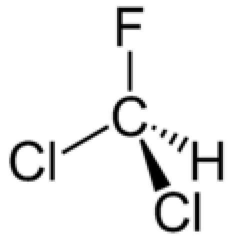
Some CFCs



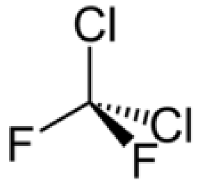
Freon-11; refrigerant



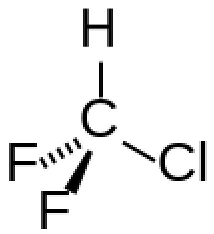
Freon-13; refrigerant
High ozone depletion potential
High global warming potential
640 year lifetime in atmosphere



Freon-21; refrigerant, propellant



Freon-12; refrigerant, aerosol spray propellant



Freon-22; refrigerant, propellant

[Lifetimes and ODPs of CFCs]
[Chlorofluorocarbons]

…fluorinated gases have lifetimes in the atmosphere of a few weeks to thousands of years

Ozone depletion in the stratosphere (anthropogenic)

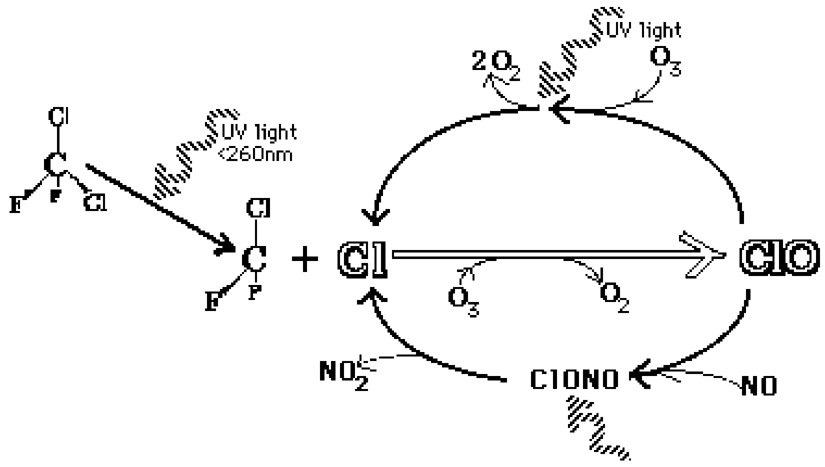
Example of the catalytic activity of chlorine in degrading ozone:

(1) $Cl + O_3 \rightarrow ClO + O_2$
(2) $ClO + O^{\cdot} \rightarrow Cl + O_2$

Overall reaction: $O_3 + O^{\cdot} \rightarrow 2O_2$

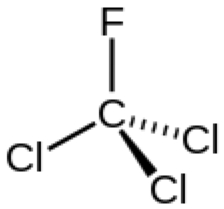
- 1 molecule of chlorine can degrade thousands of molecules of ozone before it is removed from the stratosphere

- These anthropogenic inputs disrupt the natural ozone cycle, depleting ozone before it can be replenished



Ozone chemistry

Ozone depletion potential (ODP)



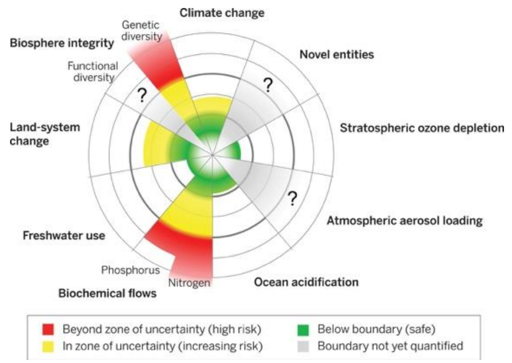
CFC-11
Freon-11
trichlorofluoromethane

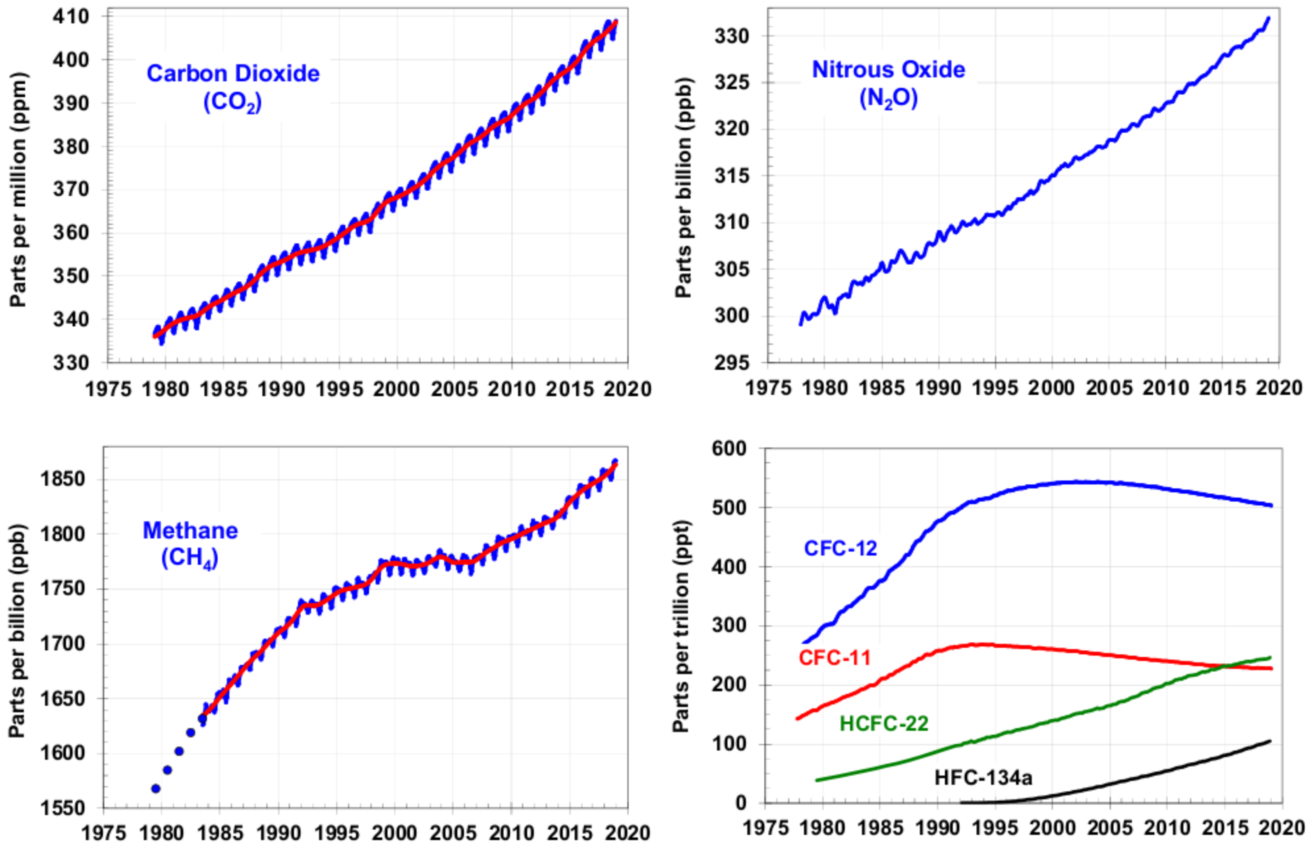
- ODP of a given gas is defined as the ratio of global loss of ozone due to the gas in question relative to the global loss of ozone due to *CFC-11*, with an ODP of 1
- Stable gases make it through to the stratosphere, some of these gases can react to degrade ozone

Gas	ODP
Trichlorofluoromethane (CCl_3F)	1
Chlorodifluoromethane ($CClF_2$-*H*)	0.05
Bromotrifluoromethane ($CBrF_3$)	15.9
Bromochlorodifluoromethane ($CClF_2$-*Br*)	7.9
Dichlorodifluoromethane ($CClF_2$-*Cl*)	1
Nitrous oxide (N_2O)	0
Carbon dioxide (CO_2)	0
Nitrogen (N_2)	0

Montreal Protocol – Ozone depletion

- Observations of hole in the South Pole in the 80s
- Protocol came into force in 1987
- Focused on the phaseout of CFCs
- Since, atmospheric levels of CFCs and other related *chlorinated hydrocarbons* have leveled off or decreased (success!)



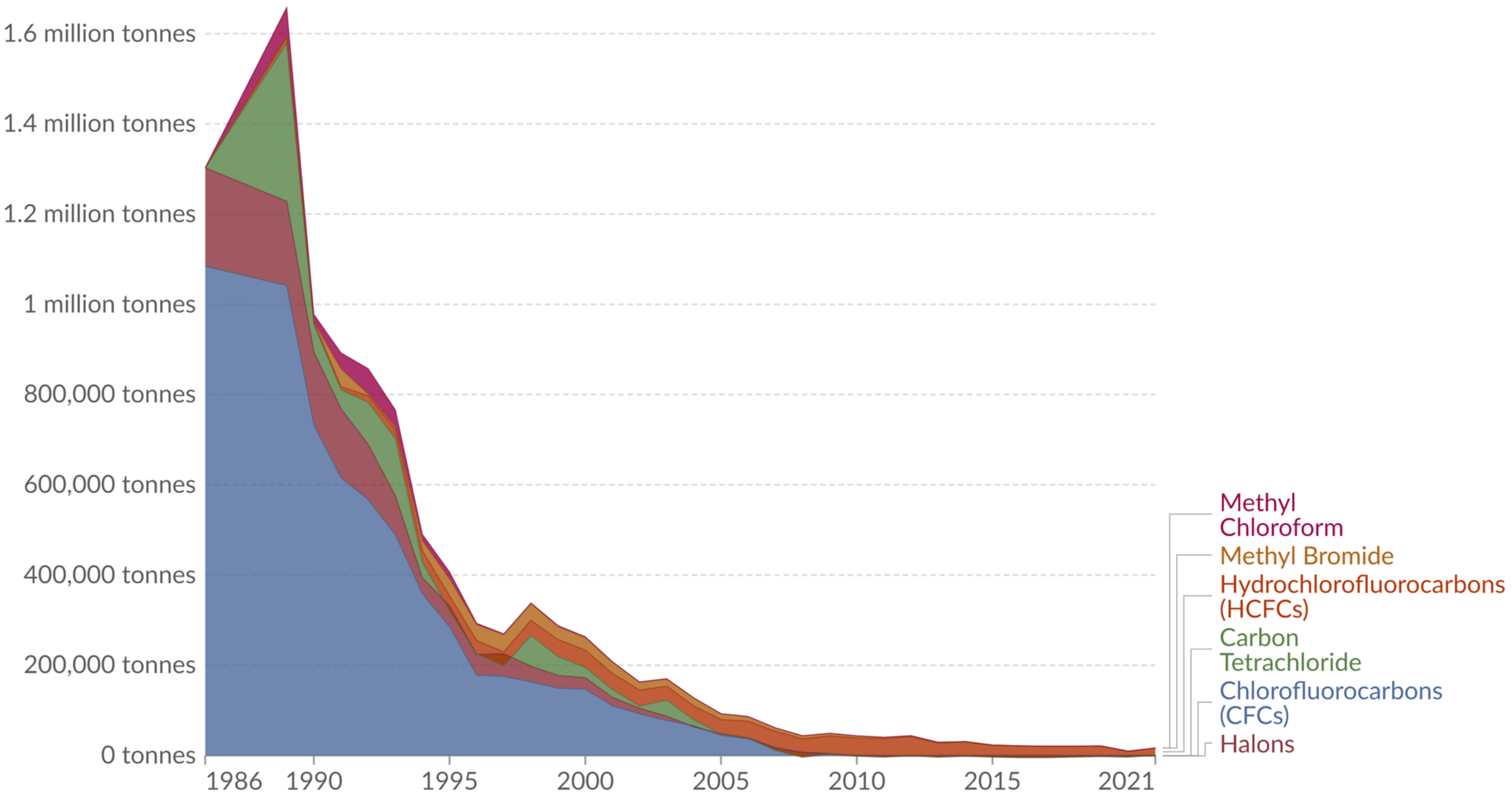


Montreal Protocol

CFCs

Emissions of ozone-depleting substances, World

Annual consumption of ozone-depleting substances. Emissions of each gas are given in ODP tonnes[1].



Data source: UN Environment Programme (2023)

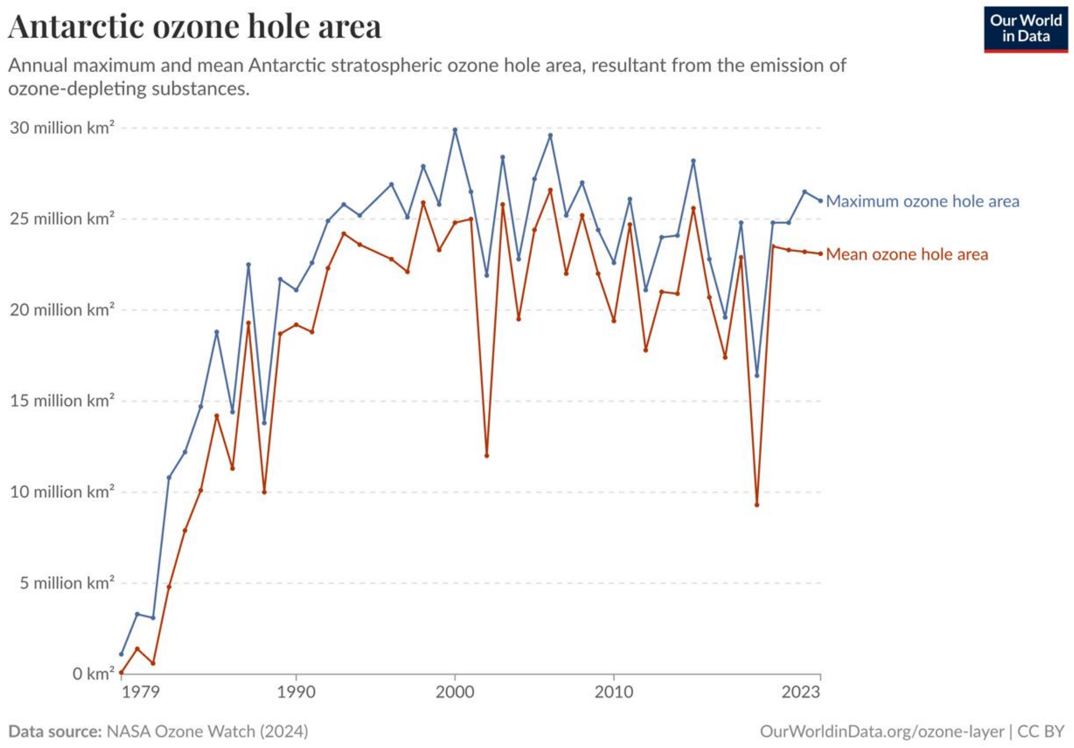
Note: In some years, gases can have negative consumption values. This occurs when countries destroy or export gases that were produced in previous years (i.e. stockpiles).

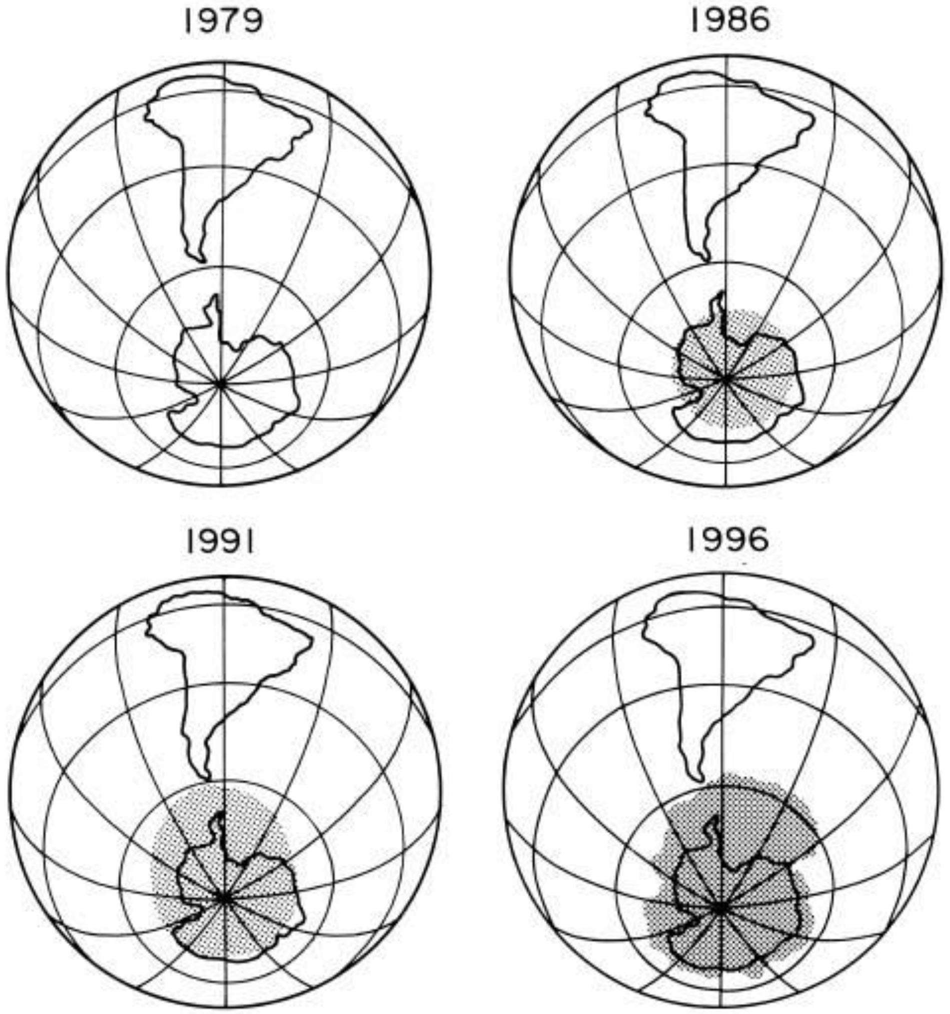
1. Ozone-depleting tonnes (ODP tonnes): Ozone-depleting tonnes measure the total potential of substances to deplete the ozone layer. Some substances that deplete the ozone layer are 'stronger' than others, meaning one tonne will cause greater damage than one tonne of another. ODP tonnes are calculated by multiplying a substance's emissions in tonnes, by its 'ozone-depleting potential'. Ozone-depleting potential measures how much depletion a substance causes relative to CFC-11, which has a value of 1.0. If one tonne of a gas caused twice the depletion of CFC-11, it would have a potential of 2.0.

Ozone layer

Ozone “hole”

- Very cold stratosphere in Antarctica
- Formation of polar stratospheric clouds
- Clouds promote formation of chemically active halogens



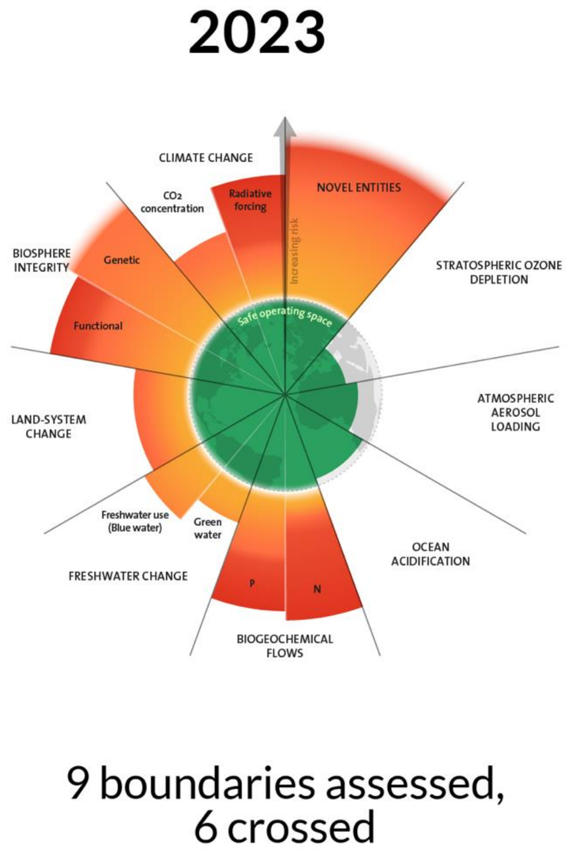


Ozone layer

Special conditions in antarctica

Is ozone depletion solved?

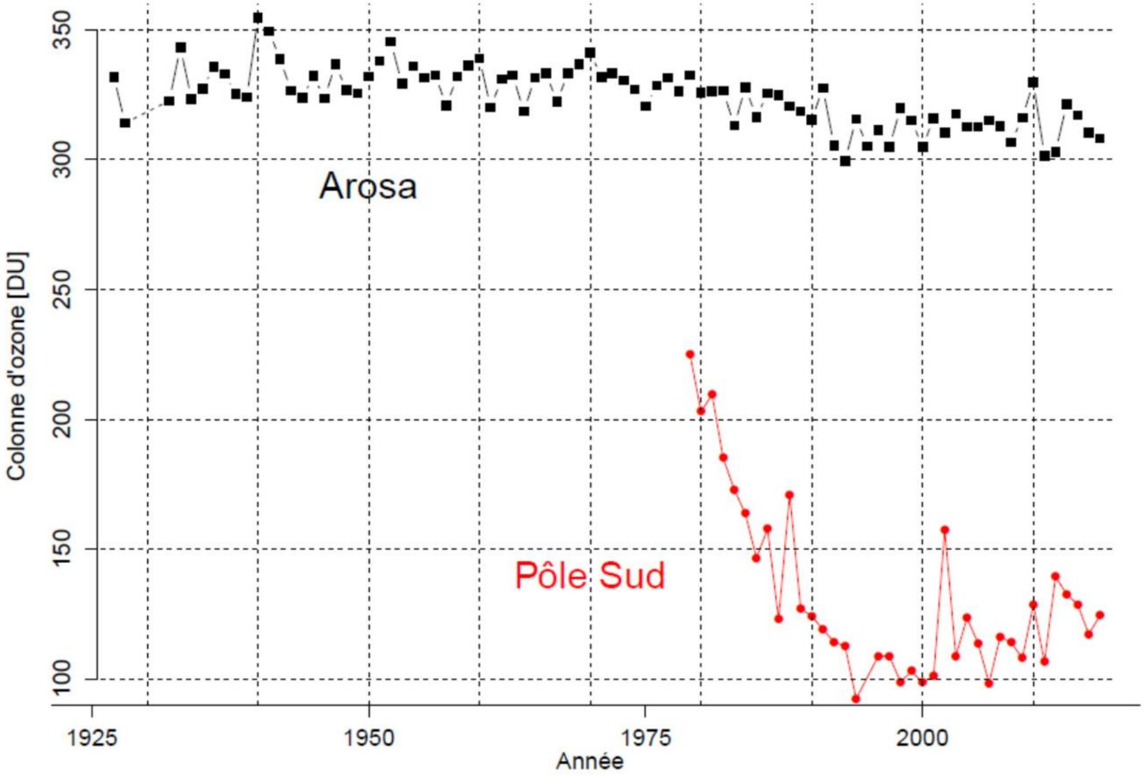
- Ozone layer depletion is **not** a transgressed planetary boundary – so all good?
- It is projected that if current policies remain, the layer will recover to pre-1980 values by 2066 for Antarctica, by 2045 for the Arctic, and by 2040 for the rest of the world
- We are on the right track thanks to the adoption of the Montreal Protocol
- The protocol targeted the phase down of many hydrofluorocarbons, (btw some of which don't destroy ozone, but do behave like GHGs)



Ozone layer recovery

Ozone monitoring

Ozone monitoring – Swiss connection



Black: time series of annual mean values of the ozone column at Arosa (GR) since 1926. Red: time series of the minimum ozone values at the South Pole since 1979. Dobson Unit corresponds to the ozone volume in the air above one square meter over the ground at normal conditions (temperature 0 °C, air pressure 1 bar).

- Swiss professor started these measurements at Arosa in 1926 (upper atmosphere)
- Lower in South Pole due to ozone hole

Ozone monitoring

Table 1. Proposed planetary boundaries.

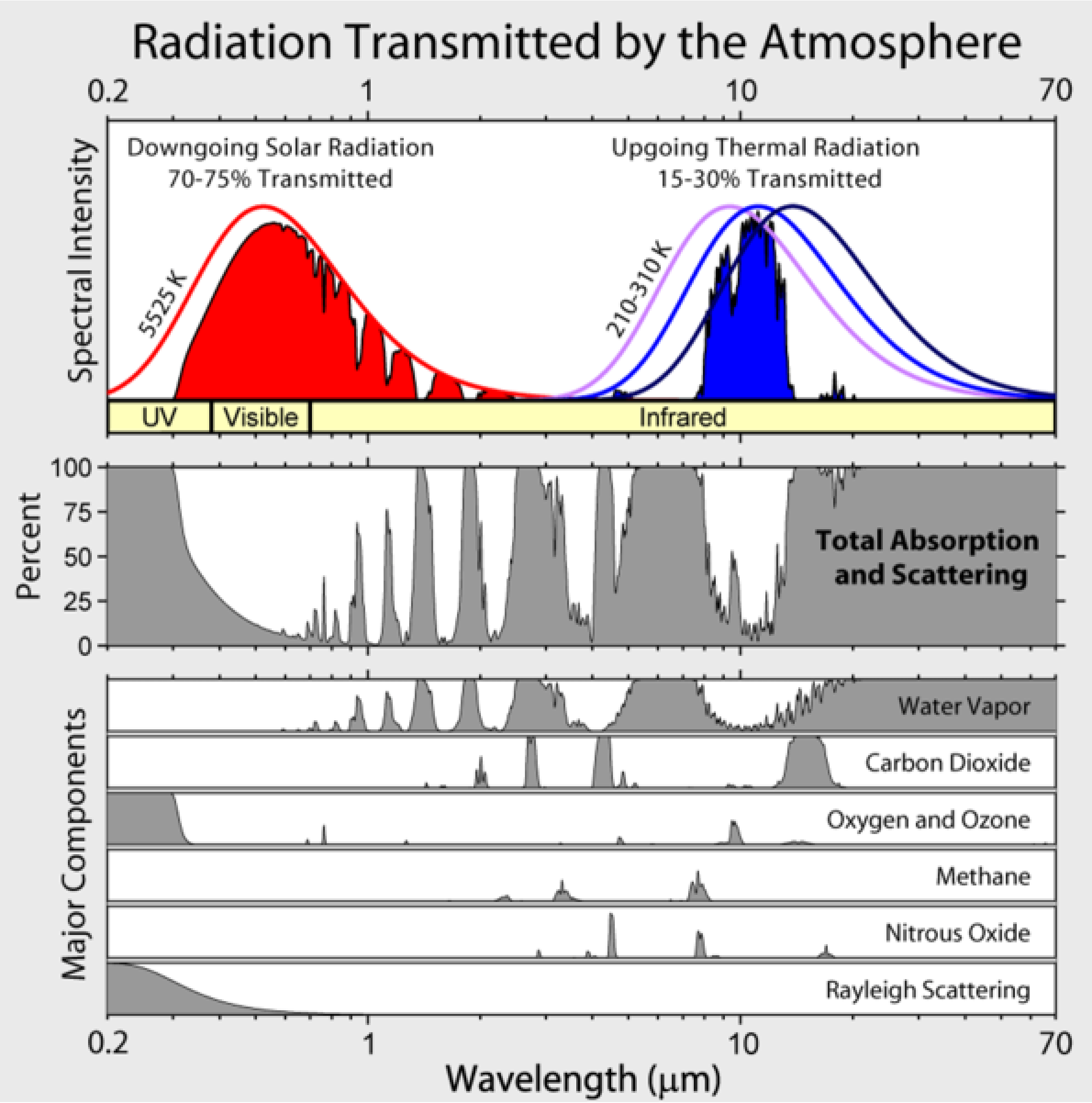
Earth System process	Control variable	Threshold avoided or influenced by slow variable	Planetary Boundary (zone of uncertainty)	State of knowledge*
Climate change	Atmospheric CO_2 concentration, ppm; Energy imbalance at Earth's surface, W m^{-2}	Loss of polar ice sheets. Regional climate disruptions. Loss of glacial freshwater supplies. Weakening of carbon sinks.	Atmospheric CO_2 concentration: 350 ppm (350–550 ppm) Energy imbalance: +1 W m^{-2} (+1.0–+1.5 W m^{-2})	1. Ample scientific evidence. 2. Multiple sub-system thresholds. 3. Debate on position of boundary.

A digression back to climate change.

Is there a connection between climate change and ozone depletion?

Ecology and Society 14(2): 32
http://www.ecologyandsociety.org/vol14/iss2/art32/

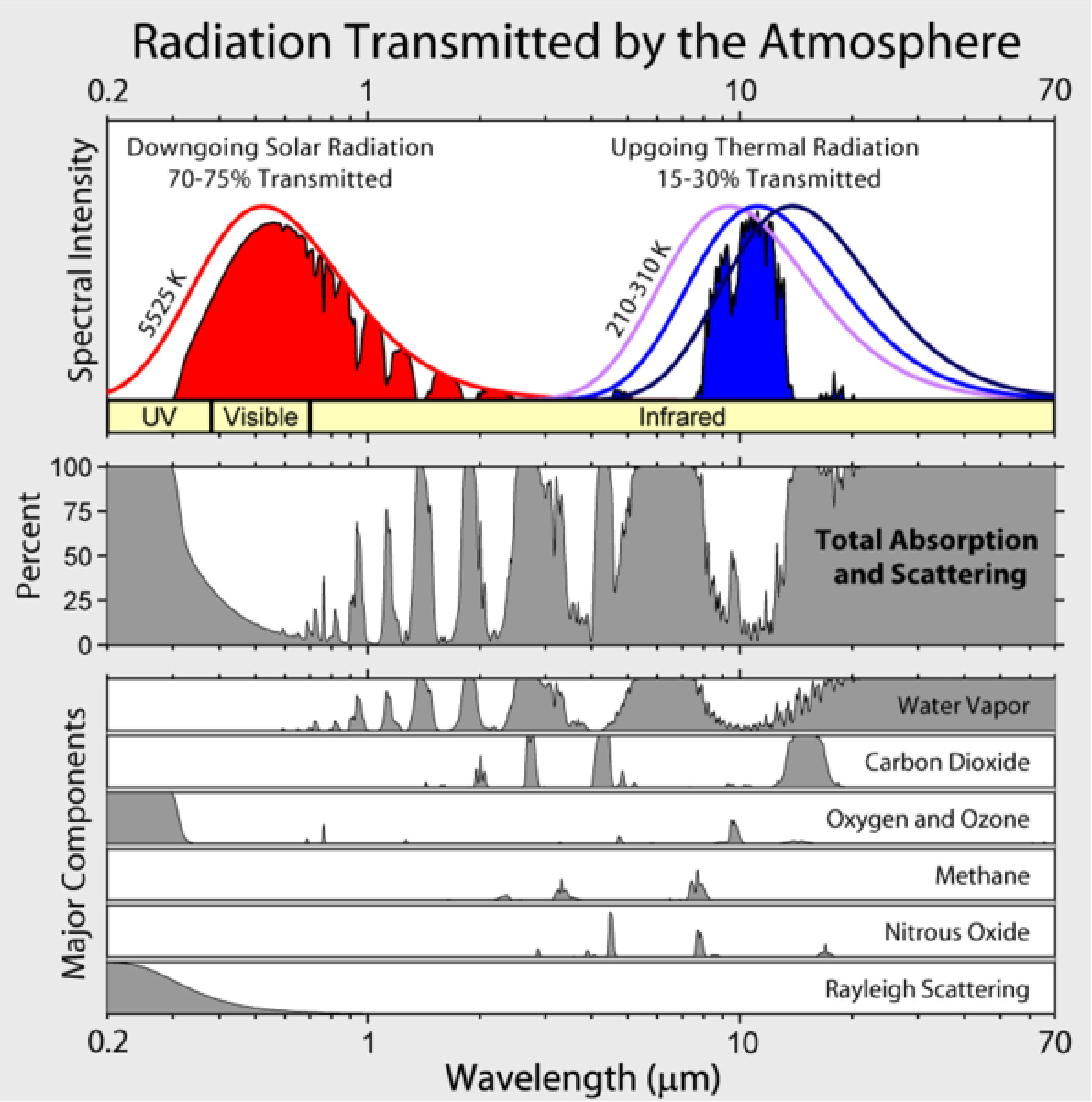
A deeper dive into spectra: heat



- Approx. 70% of solar radiation is transmitted through the atmosphere to earth
- Approx. 30% of thermal radiation (heat/IR) transmitted from earth through atmosphere into space
- The 70% that is not lost to space is absorbed and scattered by the atmosphere and clouds, partly re-directed toward earth by re-emission and scattering (warming)
- We can see the different gases and the wavelengths that they absorb

Atmospheric transmission

Closer look at CO_2 – a GHG



- Far IR (FIR): 9 µm-1 mm (where significant CO_2 absorption occurs, especially at 15 µm)
- This 15 µm is key – as this coincides with the main absorption band of CO_2! This wavelength corresponds to a significant emission from Earth (see blue spectrum at left), and effectively closes a window where this energy would otherwise escape…

Atmospheric transmission

Global warming potential (GWP)

- GWP of a given gas is expressed as a multiple of the thermal radiation that would be absorbed by the *same mass of CO_2, with a GWP of 1*
- Value depends on how strongly the gas absorbs IR, how quickly the gas leaves the atmosphere, and the time frame that is considered
- Some ODS are also GHGs…

Gas	Lifetime/ y	GWP/20 y	GWP/100 y	GWP/500 y
CO_2	/	1	1	1
CH_4	12	83	30	10
N_2O	109	273	273	130
CCl_3F	52	8321	6226	2093
CCl_2F_2	100	10800	10200	5200
*SF_6	3200	17500	23500	32600

* VERY stable, just sticks around forever, so a small amount can have a significant impact on climate change, used in electric power systems for voltage insulation

GWP

A non-comprehensive timeline of sustainability

- The Silent Spring by Rachel Carson, 1962
- Earth Day, 1970
- Greenpeace, 1971
- ~~**Phase out of CFCs (1980s) – *Montreal Protocol***~~
- "Our common future" by the UN Brundtland Commission (1987)
- **Green chemistry (1990s)**
- **Carbon as a currency – *Kyoto Protocol (early 2000s)***
- **Climate change (1.5 °C) – *Paris Agreement (2010s)***
- **Roadmap for prosperity – *UN Sustainable Development Goals (2010s)***

FILE - In this April 23, 1970, file photo, part of crowd observing Earth Day, including, youngster wearing "Let Me Grow Up:" sign on back relaxes on hilltop in Philadelphia's Fairmount Park in Philadelphia. (AP Photo)

Silent spring summary
Earth Day
Brundtland Report

What's Green Chemistry?

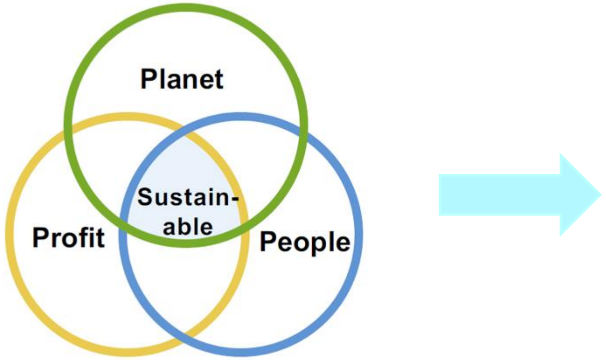
Generic chemical synthesis

A + B ⟶ AB

Reactants Product

A poorly designed reaction -

- Toxic, dangerous, uncontrolled, polluting
- Multi-step
- Low yield
- Side products/waste products
- Contaminated product
- Needs solvents
- Harsh reaction conditions



Remember me? Green Chemistry embodies these principles, safety and well-being for people and planet, while still producing the chemicals and materials needed for economic prosperity

Sustainable design at the molecular level – Green Chemistry

- Formulated in the 1990s
- Based on 12 principles or “design rules” (1998 by Paul Anastas and John Warner)
- Anastas “Father of Green Chemistry”
- Framework of green chemistry
  1. Design across all stages of the chemical life-cycle (synthesis through end of life)
  2. Design to reduce hazards of chemical products and processes
  3. Works as a cohesive system of design criteria
- Shift focus from ***exposure control*** to ***reducing hazards*** across all life cycle stages
- Successfully applied in both academia and industry

DOI: 10.1039/B918763B (Critical Review) *Chem. Soc. Rev.*, 2010, **39**, 301-312

EPFL

12 Principles of Green Chemistry

"An ounce of prevention is worth a pound of cure."
Benjamin Franklin, 1736

	Principle	Description
1	Prevention	Better to prevent waste, then clean or treat it
2	Atom Economy	Design syntheses to maximize incorporation of all materials used in process
3	Less Hazardous Chemical Synthesis	Design syntheses and generate substances with little or no toxicity
4	Designing Safer Chemicals	Chemical products that are effective in their function while reducing toxicity
5	Safer Solvents and Auxiliaries	Don't use, if you use, use non/low toxic
6	Design for Energy Efficiency	Ambient temperatures and pressures ideal

DOI: 10.1039/B918763B (Critical Review) *Chem. Soc. Rev.*, 2010, **39**, 301-312

1. **Prevention**. It is better to prevent waste than to treat or clean up waste after it is formed.
2. **Atom Economy**. Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.
3. **Less Hazardous Chemical Synthesis**. Whenever practicable, synthetic methodologies should be designed to use and generate substances that pose little or no toxicity to human health and the environment.
4. **Designing Safer Chemicals**. Chemical products should be designed to preserve efficacy of the function while reducing toxicity.
5. **Safer Solvents and Auxiliaries**. The use of auxiliary substances (e.g. solvents, separation agents, etc.) should be made unnecessary whenever possible and, when used, innocuous.
6. **Design for Energy Efficiency**. Energy requirements of chemical processes should be recognized for their environmental and economic impacts and should be minimized. If possible, synthetic methods should be conducted at ambient temperature and pressure.
7. **Use of Renewable Feedstocks**. A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable.
8. **Reduce Derivatives**. Unnecessary derivatization (use of blocking groups, protection/ deprotection, temporary modification of physical/chemical processes) should be minimized or avoided if possible, because such steps require additional reagents and can generate waste.
9. **Catalysis**. Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.
10. **Design for Degradation**. Chemical products should be designed so that at the end of their function they break down into innocuous degradation products and do not persist in the environment.
11. **Real-Time Analysis for Pollution Prevention**. Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.
12. **Inherently Safer Chemistry for Accident Prevention**. Substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires.

12 Principles of Green Chemistry

"An ounce of prevention is worth a pound of cure."
Benjamin Franklin, 1736

	Principle	Description
7	Use of Renewable Feedstocks	Renewable raw material preferred
8	Reduce Derivatives	Minimize or avoid unnecessary derivatives
9	Catalysis	Use as much as possible
10	Design for degradation	Products designed to breaks down into non-persistent chemicals at end of life
11	Real-time analysis for pollution prevention	Real time, in process monitoring and control, before hazardous substances are formed
12	Inherently safer chemistry for accident prevention	Design reactions and chemicals to minimize the risk of accidents

1. **Prevention**. It is better to prevent waste than to treat or clean up waste after it is formed.
2. **Atom Economy**. Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.
3. **Less Hazardous Chemical Synthesis**. Whenever practicable, synthetic methodologies should be designed to use and generate substances that pose little or no toxicity to human health and the environment.
4. **Designing Safer Chemicals**. Chemical products should be designed to preserve efficacy of the function while reducing toxicity.
5. **Safer Solvents and Auxiliaries**. The use of auxiliary substances (e.g. solvents, separation agents, etc.) should be made unnecessary whenever possible and, when used, innocuous.
6. **Design for Energy Efficiency**. Energy requirements of chemical processes should be recognized for their environmental and economic impacts and should be minimized. If possible, synthetic methods should be conducted at ambient temperature and pressure.
7. **Use of Renewable Feedstocks**. A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable.
8. **Reduce Derivatives**. Unnecessary derivatization (use of blocking groups, protection/ deprotection, temporary modification of physical/chemical processes) should be minimized or avoided if possible, because such steps require additional reagents and can generate waste.
9. **Catalysis**. Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.
10. **Design for Degradation**. Chemical products should be designed so that at the end of their function they break down into innocuous degradation products and do not persist in the environment.
11. **Real-Time Analysis for Pollution Prevention**. Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.
12. **Inherently Safer Chemistry for Accident Prevention**. Substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires.

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