MC-226
Introduction to Environmental Studies

Lecture (Topic) 4: A Study of Global Climate

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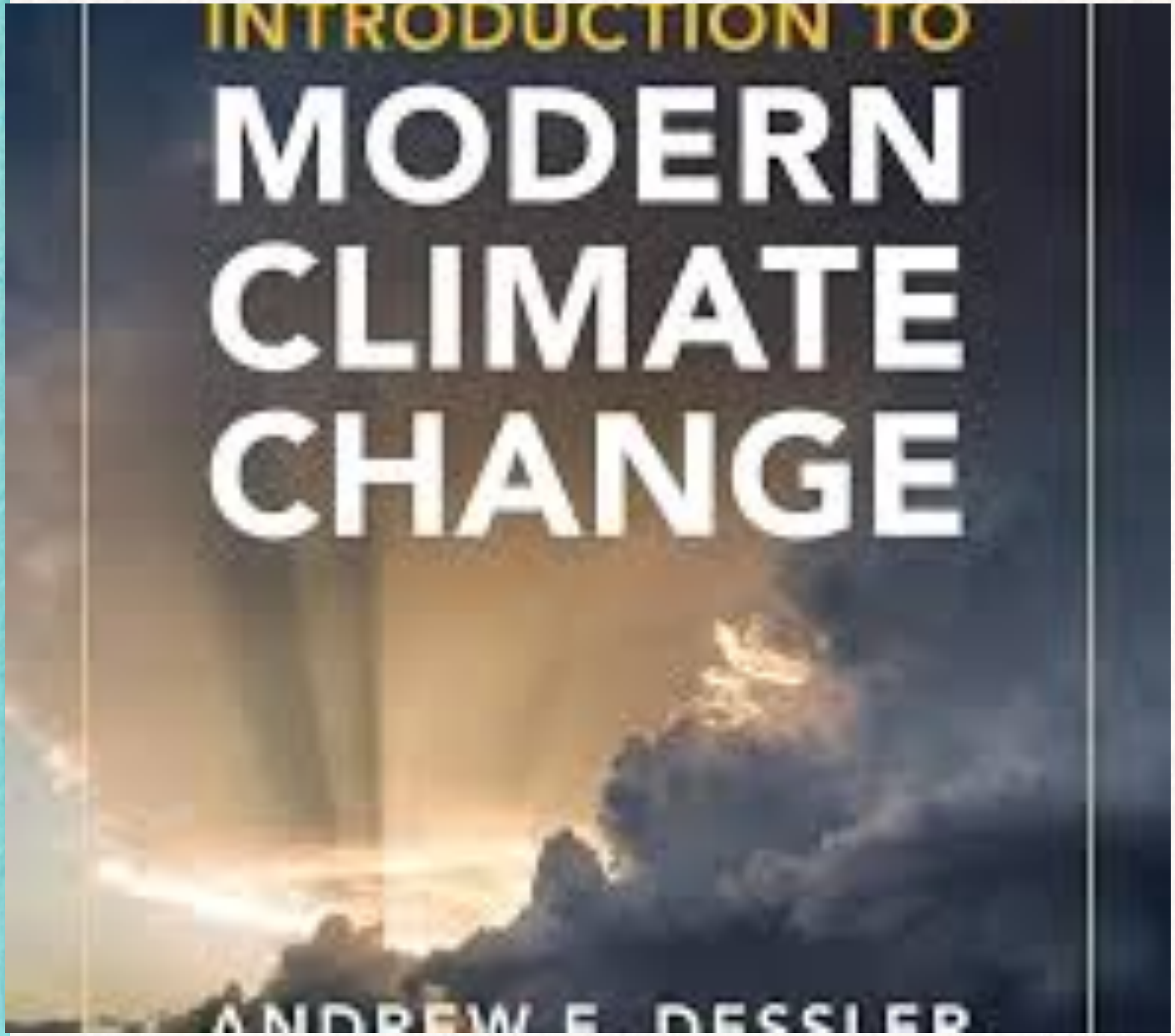
DA-IICT

Reference

Andrew E. Dessler, Introduction to Modern Climate Change, Third Edition, Cambridge University Press, 2022

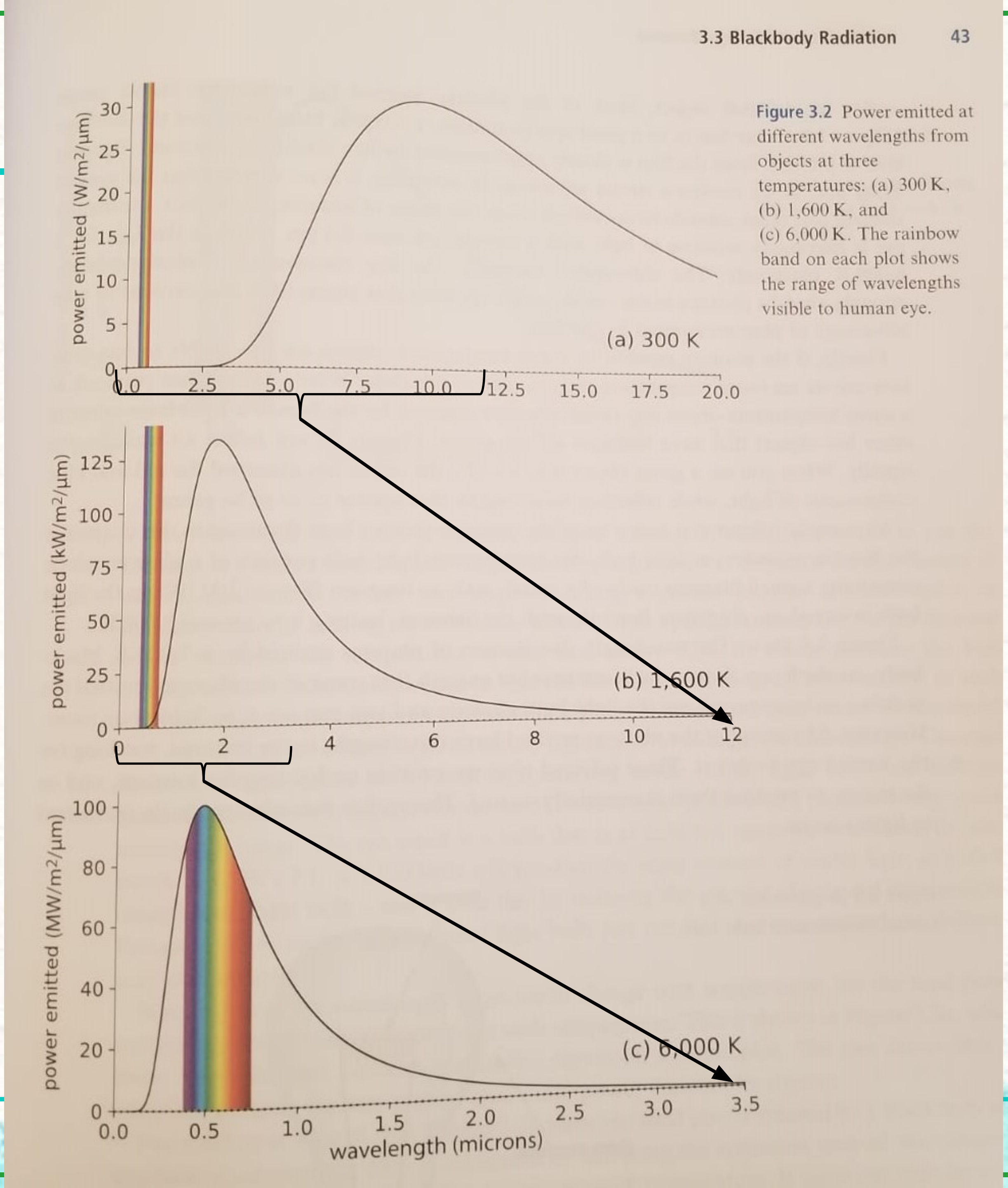


Everything Emits Photons

- We know that the Sun, the lamp in your room, your computer and the phone screen – all either emit or reflect the photons. That is why we see them
- However, these are not the only objects that emit the photons. Everything around you is constantly emitting the photons.
- If so, why does not everything glow like a light-bulb?
- This is because the wavelength emitted is determined by the object’s temperature
- As the temperature increases, the peak of the emissions spectrum as a function of the wavelength moves toward left, i.e., the peak occurs at *lower* wavelengths

Power Emitted at Different Wavelengths

- Why humans perceive an object at $1600K$ to have a reddish glow?



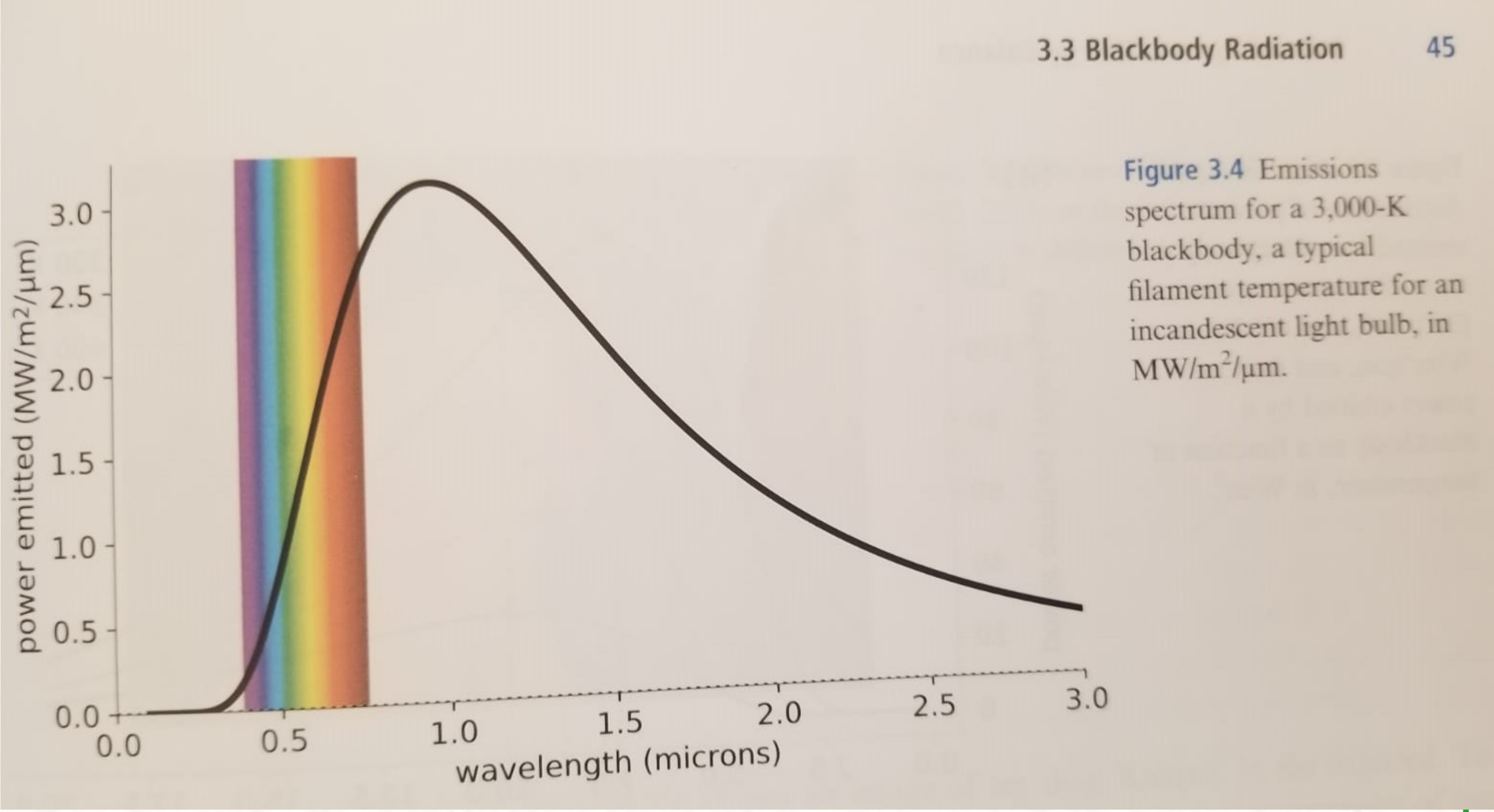
Wien's Displacement Law and Solar Emission Spectrum

- Denote $\lambda_{\max}$ as the wavelength of the photon corresponding to the peak of the emissions spectrum
- Wien's Displacement Law: $\lambda_{\max} = \frac{2897}{T}\,\mu m$, where T is the temperature in Kelvin
- The Sun's emission spectrum closely resembles that of a 6000K blackbody
  - No wonder:
    - the eyes of the humans and the other animals have evolved to see this range of wavelengths
      - Our eyes are maximally sensitive to the wavelength near 0.5 μm, which is the wavelength $\lambda_{\max}$ corresponding to the peak of the emissions spectrum of a $6000K$ blackbody
    - The chlorophyll molecule, the key component of the photosynthesis, strongly absorbs the photons with the visible range of the wavelength
      - This shows that the plants have also evolved to take advantage of the photons emitted by the Sun

Remarks

- If the photons emitted by the room temperature objects are not visible to our eyes, how can we see them?

- The emissions spectrum of an incandescent bulb:
  - Why they have a poor efficiency
  - How can it be enhanced?
  - Why the LED bulbs have a better efficiency in comparison?



Remarks

- In incandescent bulbs, electricity flows through a filament, which heats up and emits light. However, a significant amount of energy is lost in the form of heat due to the high resistance of the filament. This results in a low conversion efficiency, with only about 5-10% of the electrical energy being converted into visible light.

- The LEDs use a different mechanism called electroluminescence, which involves the emission of light from a semiconductor material when a current is passed through it. Unlike incandescent bulbs, LEDs do not use a filament, so there is no resistance and hence no significant energy loss due to heat. Instead, they use a small semiconductor chip that emits light when electrons pass through it. This results in a much higher conversion efficiency, with up to 80% of the electrical energy being converted into visible light.

- The CFLs use a mechanism called fluorescence, which involves the conversion of ultraviolet light into visible light. CFLs contain a small amount of mercury vapor that emits ultraviolet light when a current is passed through it. The ultraviolet light then strikes a phosphor coating on the inside of the bulb, causing it to fluoresce and emit visible light. This process requires much less electrical energy to produce the same amount of visible light.

Stefan-Boltzmann Equation

- The total power emitted by a blackbody increases with the temperature, as formulated by the Stefan-Boltzmann Equation

$$\frac{P}{a} = \sigma T^4$$

  - $\frac{P}{a}$ is the power emitted per unit surface area (P is the power emitted in Watts and a is the total surface area in square-meter)
  - $\sigma = 5.67 \times 10^{-8} \frac{W}{m^2K^4}$ is the Stefan-Boltzmann constant, and
  - T is the temperature in Kelvin

- Applications: emitted power can be measured by a power meter, which can, then, be converted to the temperature (heat-seeking missiles, thermometer to measure the temperature of your body, etc.)

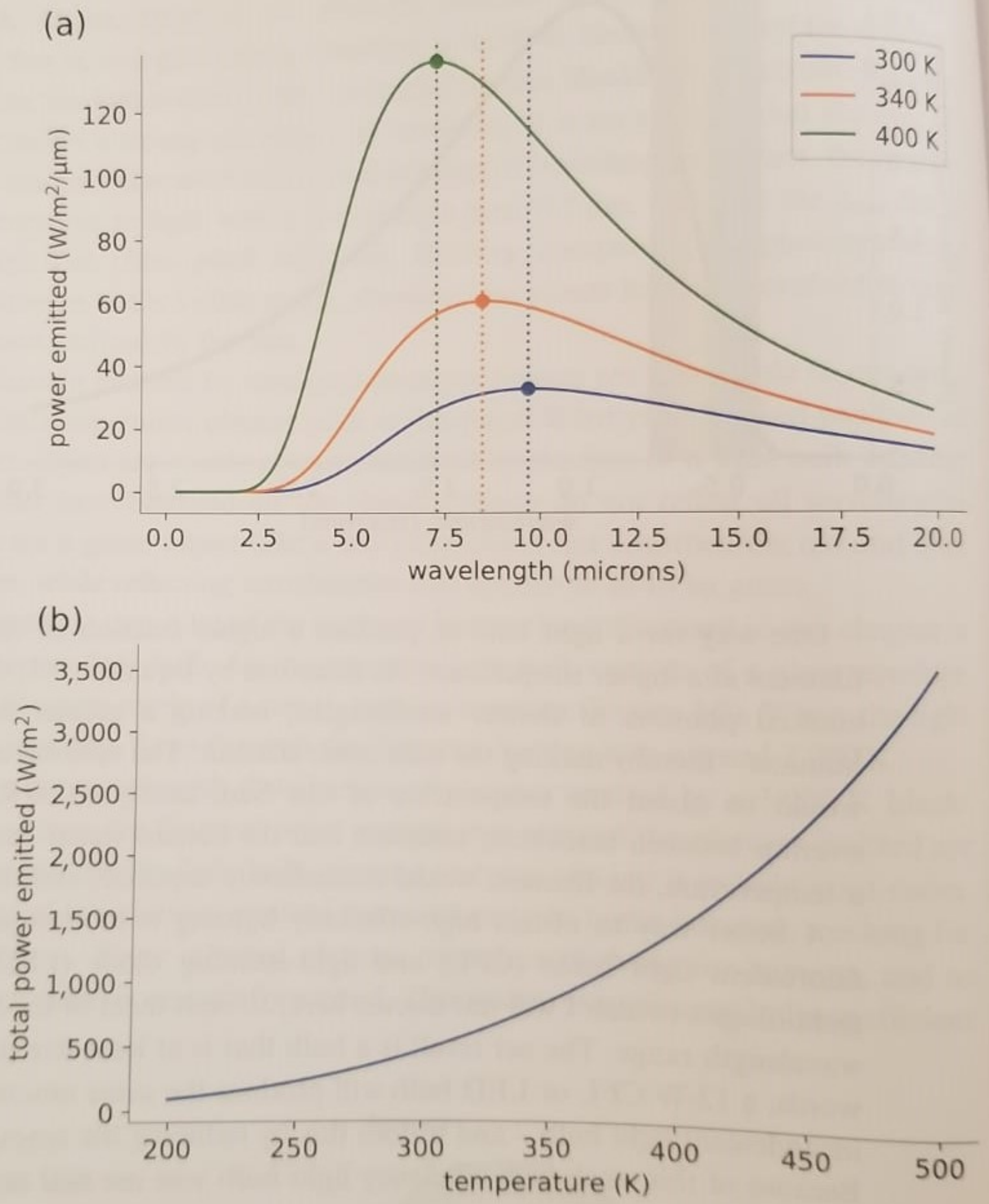


Figure 3.5 Plots of (a) the distribution of power emitted by a blackbody at three different temperatures [illegible] K), in W/m²/μm, and (b) total power emitted by a blackbody as a function of temperature, in W/m².

How fast does a basketball at the room temperature lose the energy?

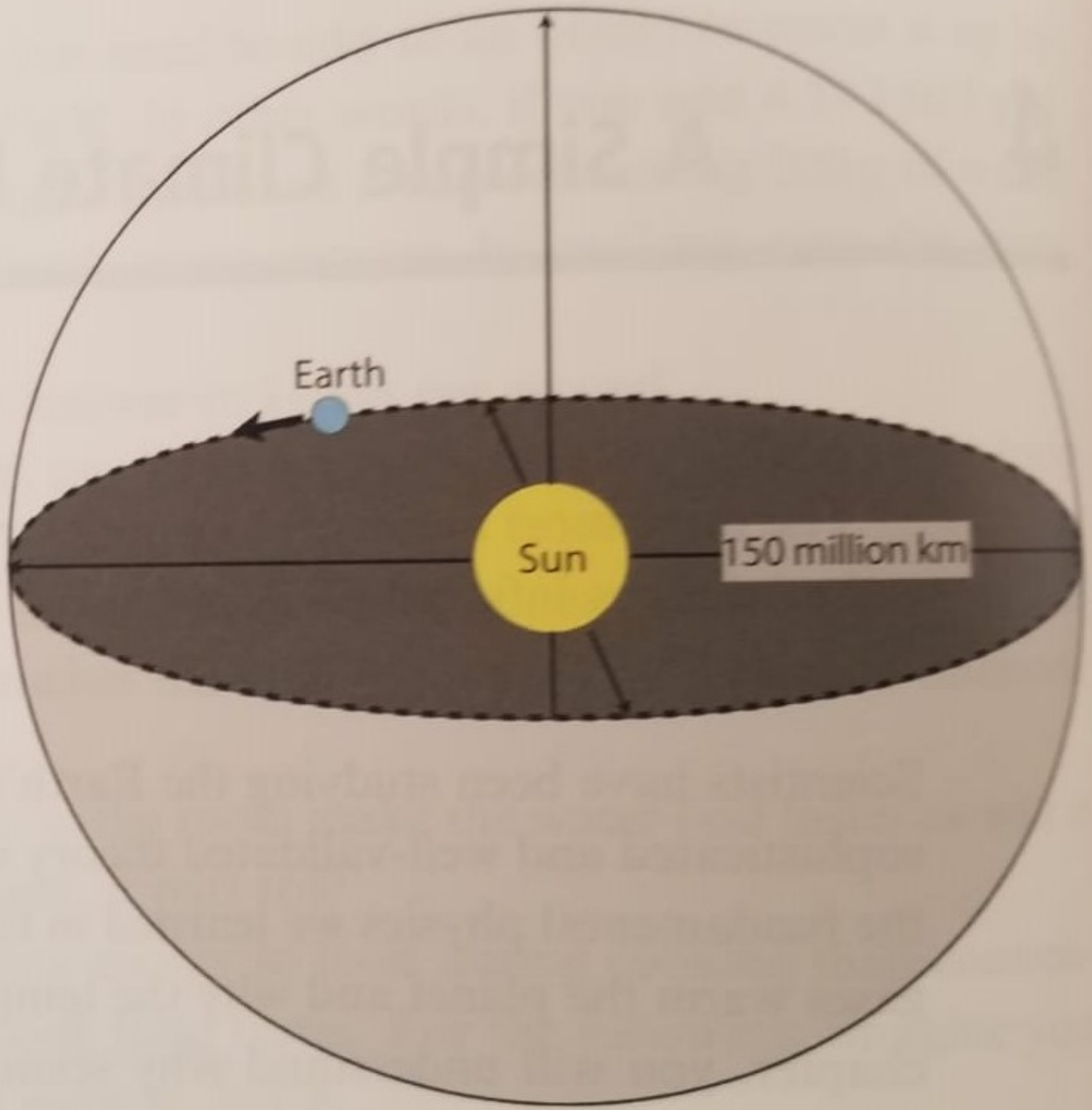
- At room temperature, $T = 300K$, therefore, $\frac{P}{a} = \sigma T^4 = \sigma(300)^4 = 460 \frac{W}{m^2}$
- Let's say, the radius of the basketball is r = 5 inches (a little less than half a foot); the surface area $a = 4\pi r^2 = 0.2\ m^2$
- Therefore, the basketball is emitting energy at a rate of $P = 460 \times 0.2 = 92$ Watts
- This is the same energy emitted every second by a typical lightbulb!

How does an oven cook the food inside?

- A short answer: because it is hot inside
- However, it is not the air inside the oven which is hot (air does not conduct the heat that well)
- When the electric oven is turned on and its heating element starts glowing red, it is generating a tremendous amount of power, in the order of thousands of Watts
- The emitted photons get absorbed by the walls of the oven and so they also heat up
- After a while, they reach a temperature of $500K$ and radiate close to $3000\ W/m^2$
- A bowl of food item you want to bake has a surface area of $0.1\ m^2$ and therefore, it absorbs roughly 300 Watts of radiated energy
- The bowl of food also emits radiation, but due to its lower temperature, it would be emitting close to $300\ \frac{W}{m^2}$, i.e., a power of 30 Watts
- Since the power emitted out is less than the power absorbed, the foot heats up and gets cooked

Solar Radiation

Figure 4.1 Solar constant calculation:
A hypothetical sphere (gray) surrounding the Sun has a radius equal to the Earth's orbit (dashed line); all radiation emitted by the Sun (black arrows) falls on this sphere.



- Sun generates a power of $P_{SUN} = 3.8 \times 10^{26}$ Watts
- Earth is at a distance of $R_{e,s} = 150$ million km from the Sun
- Therefore, the surface area of the sphere on which the Earth is located is $4\pi R_{e,s}^2$
- The intensity of the solar radiation at the Earth's orbit: $\frac{P_{SUN}}{4\pi R_{e,s}^2} = 1360\ W/m^2$, here S is called the Solar Constant for the Earth

- The total incident sun energy on the surface of the Earth: $S \times \pi R_e^2 = 175000$ TW
  - The human civilization needs only 20 TW, which is about 0.01% of the above
- On a per square-meter basis, $\frac{S \times \pi R_e^2}{4\pi R_e^2} = \frac{S}{4}$
- The Earth's albedo $\alpha = 0.3$, i.e., a fraction $1 - \alpha$ of the incident photons are absorbed by the Earth
- Therefore, the incident energy on the Earth per unit area equals $E_{in} = S \times \frac{1-\alpha}{4} = 238 \frac{W}{m^2}$
- From Stefan-Boltzmann's Law, $T = \sqrt[4]{\frac{S(1-\alpha)}{4\sigma}} =$ 255 K, which is -18^o C, about 33^o colder than the actual surface temperature of the Earth

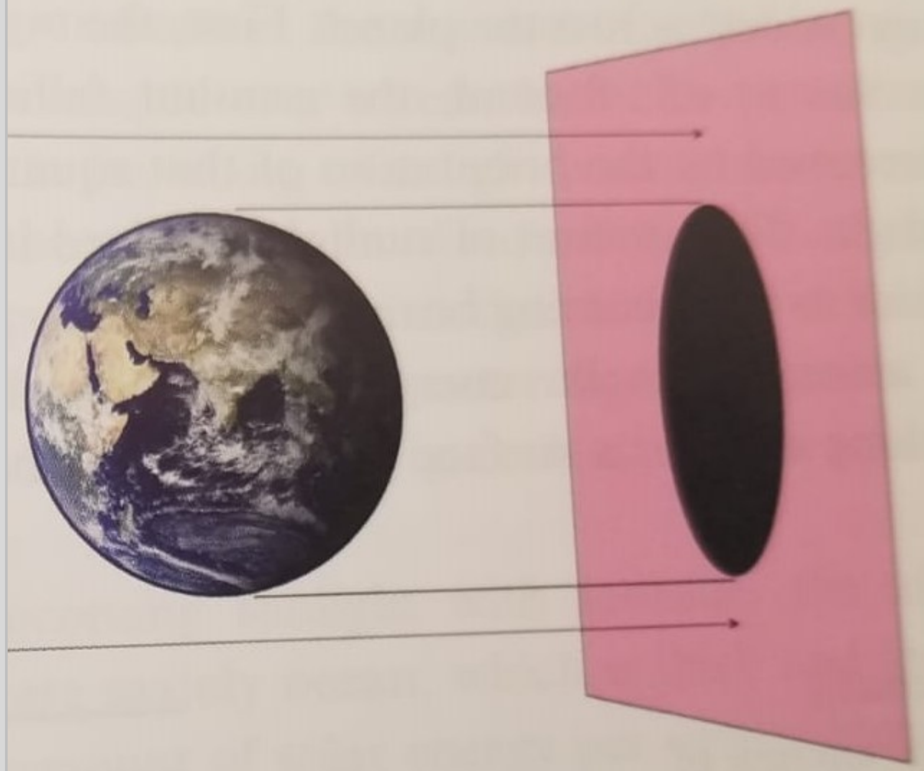
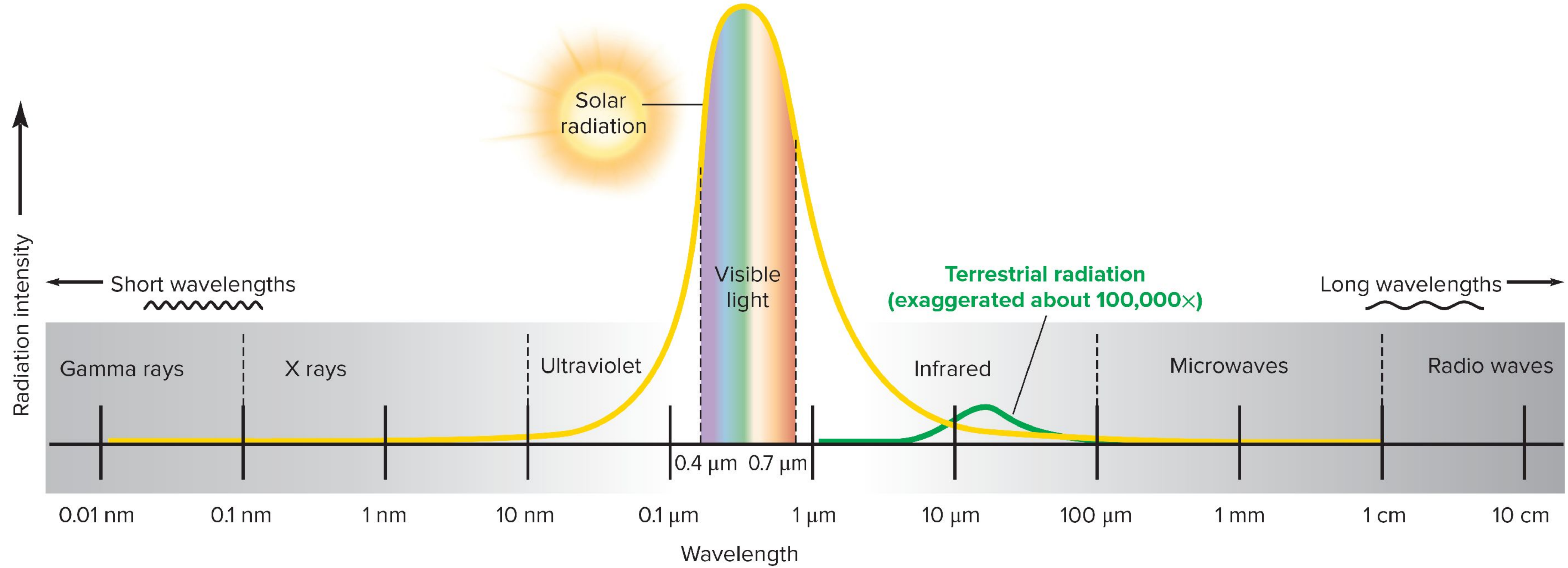


Figure 4.2 The Earth is casting a shadow on a screen placed right behind it because it blocks sunlight. The total amount of solar energy falling on the Earth is the same as what would have fallen into the shadow area. Photo of the Earth from Visible Earth, part of the EOS Project Science Office at NASA Goddard Space Flight Center: https://visibleearth.nasa.gov/images/57723/the-blue-marble/57727l.



▲ **FIGURE 2.13** The electromagnetic spectrum. Our eyes are sensitive to visible-light wavelengths, which make up nearly half the energy that reaches the earth's surface (represented by the area under the "solar radiation" curve). Photosynthesizing plants use the most abundant solar wavelengths (light and infrared). The earth reemits lower-energy, longer wavelengths (shown by the "terrestrial radiation" curve), mainly the infrared part of the spectrum.

$$T = \sqrt[4]{\frac{S(1-\alpha)}{4\sigma}} \times 2 = 255\sqrt[4]{2} = 303 \text{ K, or } 30^o \text{ C}$$

Thus, the atmosphere is Earth's blanket. It warms the Earth

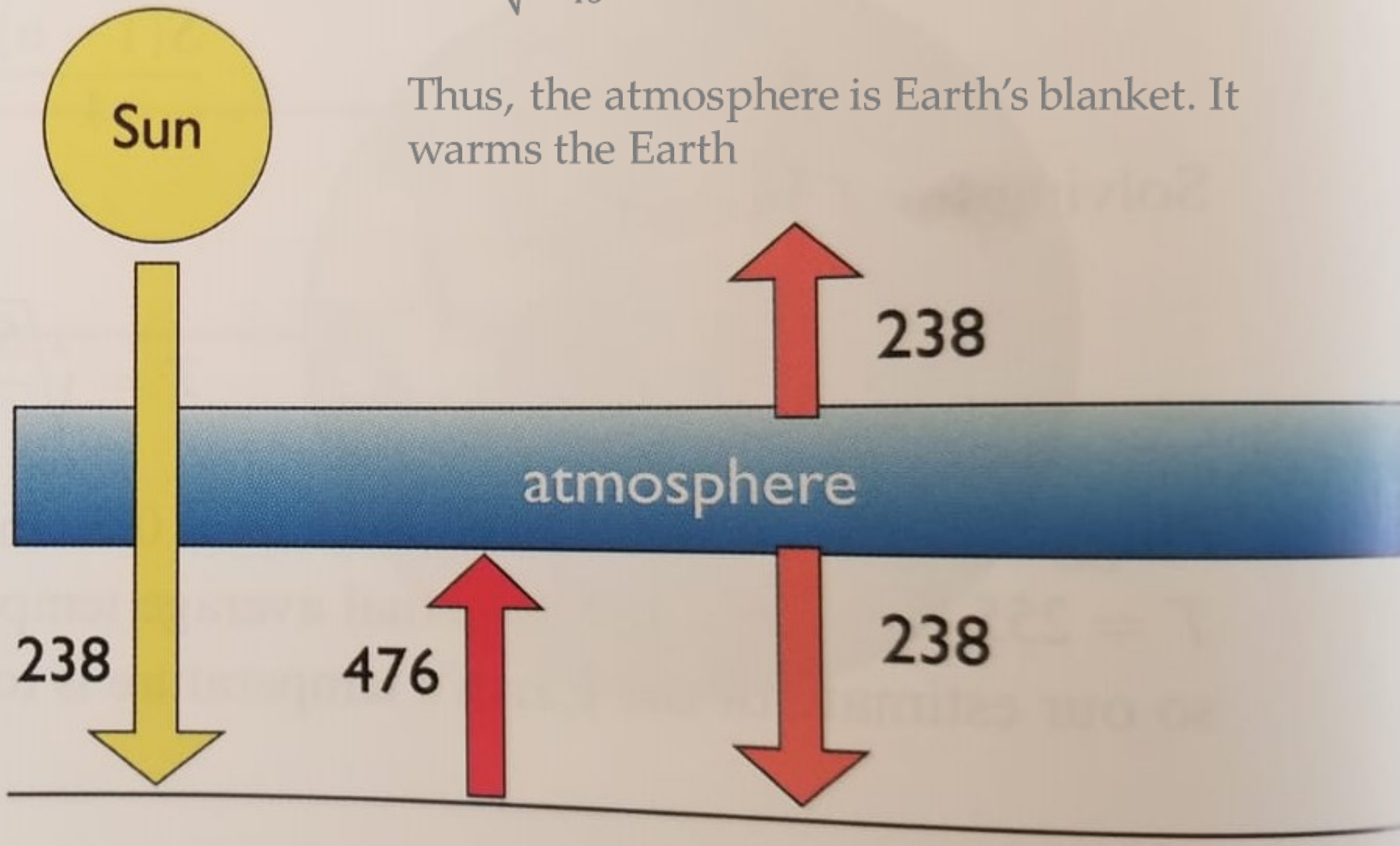
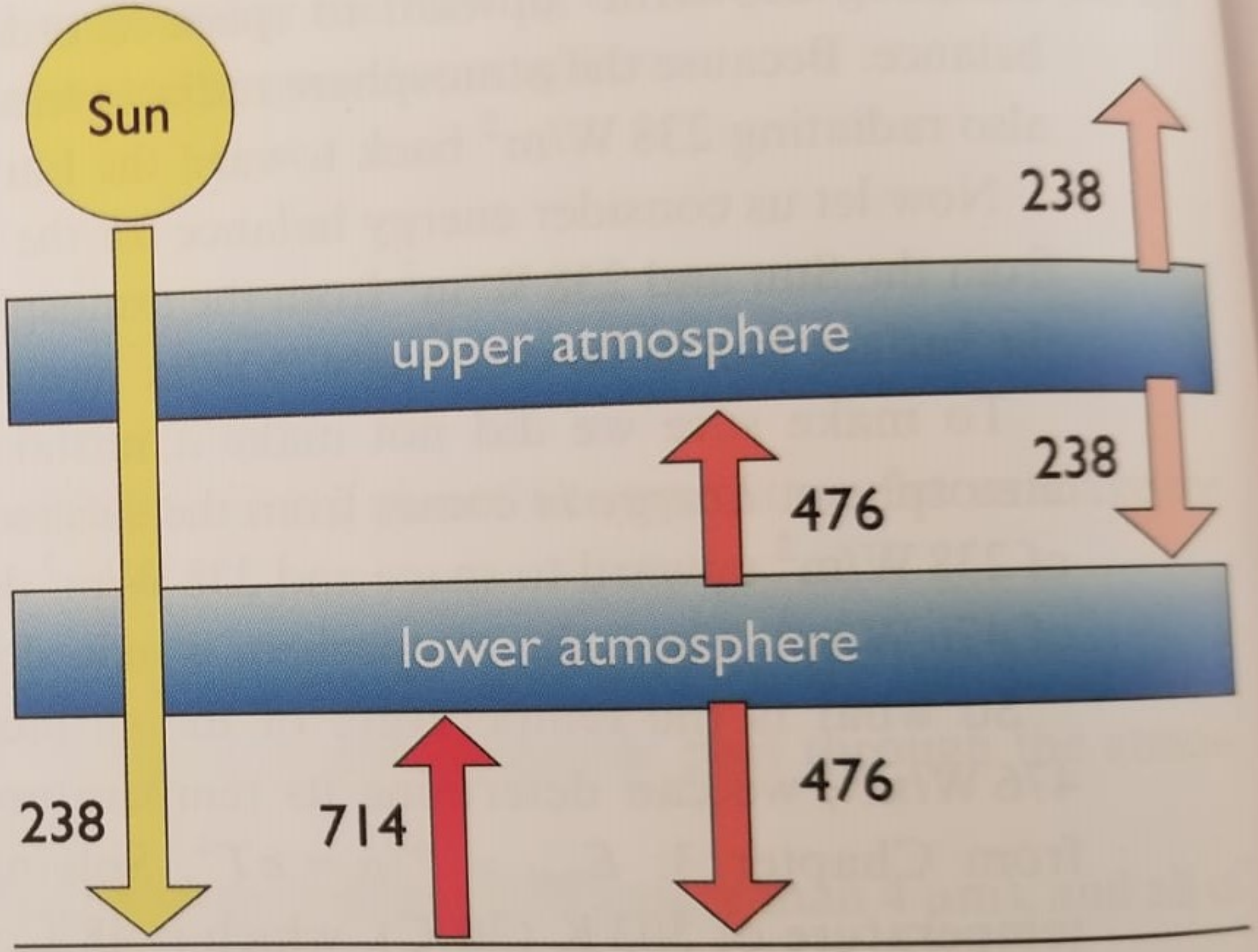


Figure 4.5 Schematic of energy flow on a planet with a one-layer atmosphere. The atmosphere is represented by a single layer that is transparent to visible photons but absorbs all infrared photons that fall on it. The arrows show global average energy flows with values in W/m^2, which are based on our Earth's values of solar constant and albedo.

Figure 4.6 Schematic of energy flow on a planet with a two-layer atmosphere, with values in W/m^2, which are based on our Earth's values of solar constant and albedo.



How to obtain the number 714 that the lower layer receives from the Earth's surface?

Answer: 476 + 476 = 952 that it is radiating upward+downward, minus 238 that the lower layer receives from the upper layer

$$T = \sqrt[4]{\frac{S(1-\alpha)}{4\sigma} \times \frac{714}{238}} = 255\sqrt[4]{3} = 335\text{ K, or } 62^{o}\text{ C}$$

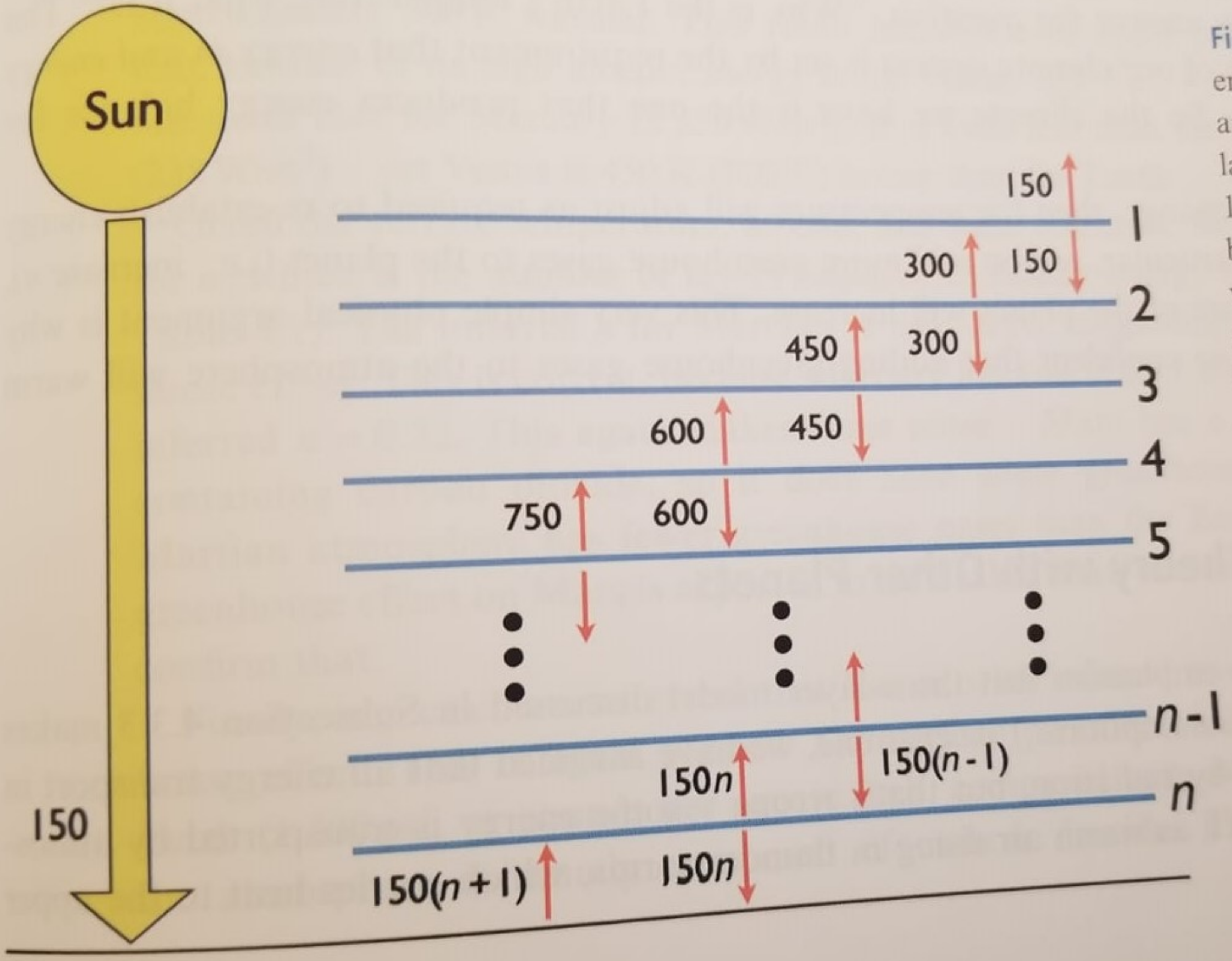


Figure 4.7 Schematic of energy flow on a planet with an n-layer atmosphere; layers are numbered from 1 to n (topmost to bottommost layers), with values in W/m^2. Fluxes assume a solar constant of 2,000 W/m^2 and an albedo of 0.7.

$$\boxed{\frac{S(1-\alpha)}{4} = 150\ \mathrm{W/m^2}}$$

$$\boxed{T = \sqrt[4]{\frac{S(1-\alpha)}{4\sigma} \times (n+1)}}$$

Remarks

- The temperature of the Earth is determined by the requirement that the energy in from the Sun should equal the energy out from the outermost layer of the atmosphere
- The number of layers n represents the amount of greenhouse gases in the atmosphere
- If either n or α changes, assuming S remains constant, the temperature will adjust to reestablish the energy balance
- An increase in the greenhouse gases, thus, has the effect of increasing the temperature of the Earth

Table 4.1 **Data on the four inner planets in our Solar System**

Planet	Solar constant (W/m^2)	Albedo	*Energy in* (W/m^2)	Observed surface temperature (K)	Inferred *n*
Mercury	10,000	0.1	2,250	452	0.052
Venus	2,650	0.7	199	735	82
Earth	1,360	0.3	238	289	0.65
Mars	580	0.15	123	227	0.22

Composition of Earth's Atmosphere

- Approximately 99.95% of the atmosphere comprises the following gases, which are not the greenhouse gases
  - Nitrogen N_2: 78%
  - Oxygen O_2: 21%
  - Argon Ar: 1%
- About 0.25% of the atmosphere is water vapor
  - Water vapor is more abundant near warm tropics and less near the colder polar regions
- The remaining 0.05% comprises mostly the following greenhouse gases
  - Carbon Dioxide CO_2: 0.041% or 410 ppm (increasing by about 2 ppm every year)
  - Methan CH_4: 1.87 ppm
  - Nitrogen Oxide N_2O: 0.32 ppm
  - Ozone: in several parts per billion
  - Halocarbons: in several parts per billion

Table 5.1 **Greenhouse-gas metrics**

Species	Lifetime	Global warming potential	Increase in abundance since pre-industrial times
Carbon dioxide	500 years	1	130 ppm
Methane	12.4 years	32	1.1 ppm
Nitrous oxide	109 years	260	75 ppb
Halocarbons	Years to millennia	100s to 1,000s	

ppb, parts per billion

Methane produced by

1. livestock (cattle, goats, sheep, whose digestive systems produce methane which gets released into the atmosphere by both the ends of the animal)
2. Bacterial processes in the landfills and other waste dumps
3. Emissions from rice farms (again through bacterial processes)
4. From petrochemical industry, natural gas wells, geological coal mines
5. Burning of forests and other biomass at insufficient temperature

Photosynthesis:

$$CO_2 + H_2O + \text{Sunlight} \rightarrow CH_2O + O_2$$

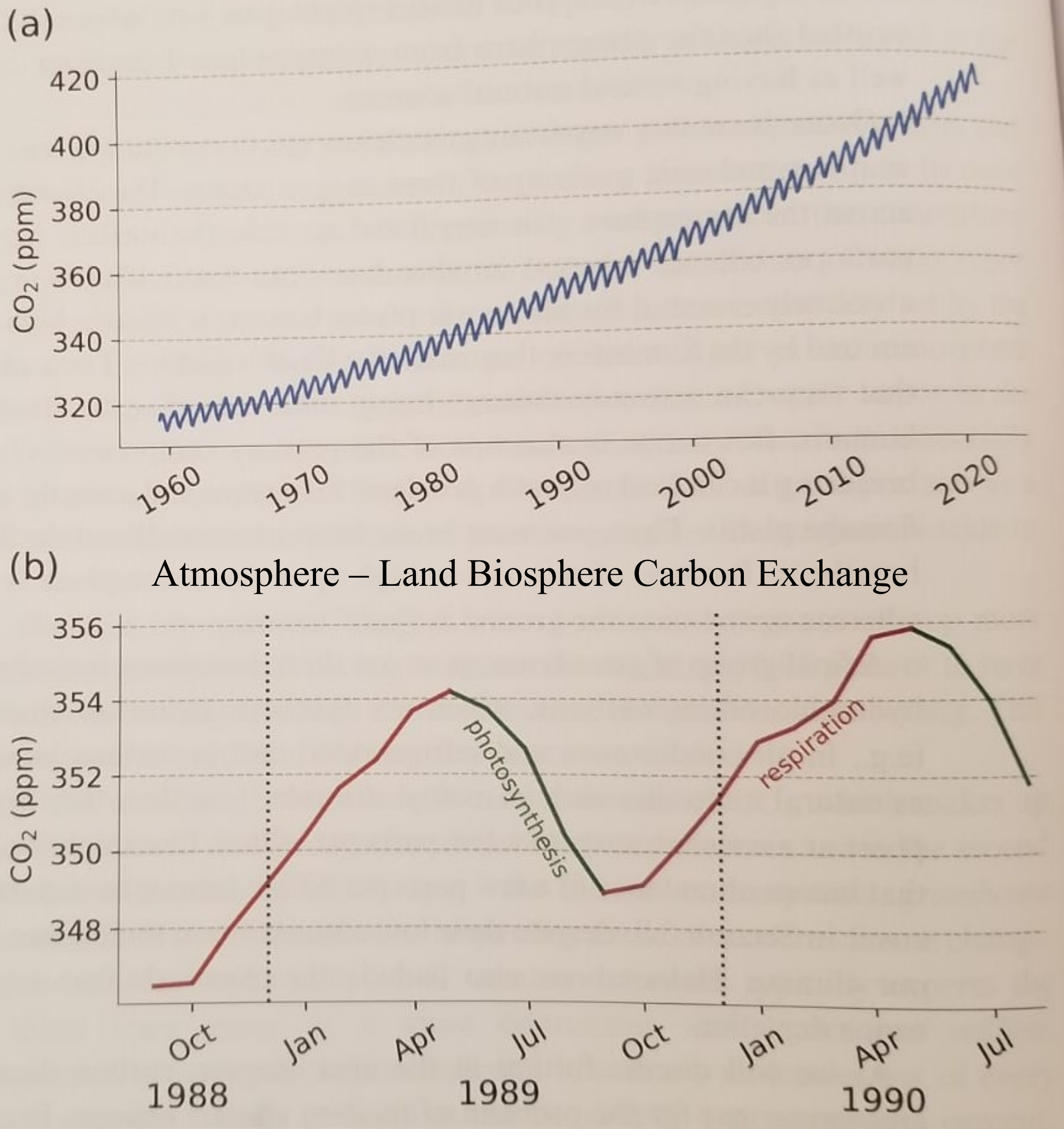
- Stores the solar energy in the carbohydrate (e.g., sugar) molecules
- Releases the oxygen in the atmosphere
- Absorbs the carbon dioxide from the atmosphere

Respiration:

$$CH_2O + O_2 \rightarrow CO_2 + H_2O + \text{Energy}$$

- Burns the carbohydrates to release the stored (solar) energy
- Releases the carbon dioxide in the atmosphere

Figure 5.1 (a) The record of atmospheric carbon dioxide since the middle of the twentieth century. (b) Close-up of two years: fall 1988 through fall 1990. Periods dominated by photosynthesis are green and periods dominated by respiration are brown. Data measured at Mauna Loa, Hawaii by Dr. Pieter Tans, NOAA/GML and Dr. Ralph Keeling, Scripps Institution of Oceanography. Data downloaded from the NOAA Earth System Research Laboratory/ Global Monitoring Division (www.esrl.noaa.gov/gmd/ccgg/trends/data.html, retrieved November 29, 2020).



Atmosphere – Ocean Carbon Exchange

- Carbon dioxide readily dissolves in the water and reacts with water to form carbonic acid:

$$\text{Process A: } CO_2 + H_2O \rightarrow H_2CO_3$$

- Similar to the reversal of the photosynthesis, the above process also has an inverse by which CO_2 is released back to the atmosphere:

$$\text{Process B: } H_2CO_3 \rightarrow CO_2 + H_2O$$

- Carbon Cycling:
  - Every year, photosynthesis removes 110 GtC from the atmosphere and respiration adds 110 GtC back to the atmosphere
  - Similarly, Process A removes 60 GtC from the atmosphere and into the oceans and Process B adds those 60 GtC back from the oceans
    - GtC: Giga-tonnes of Carbon, where one tonne is 1000 kg

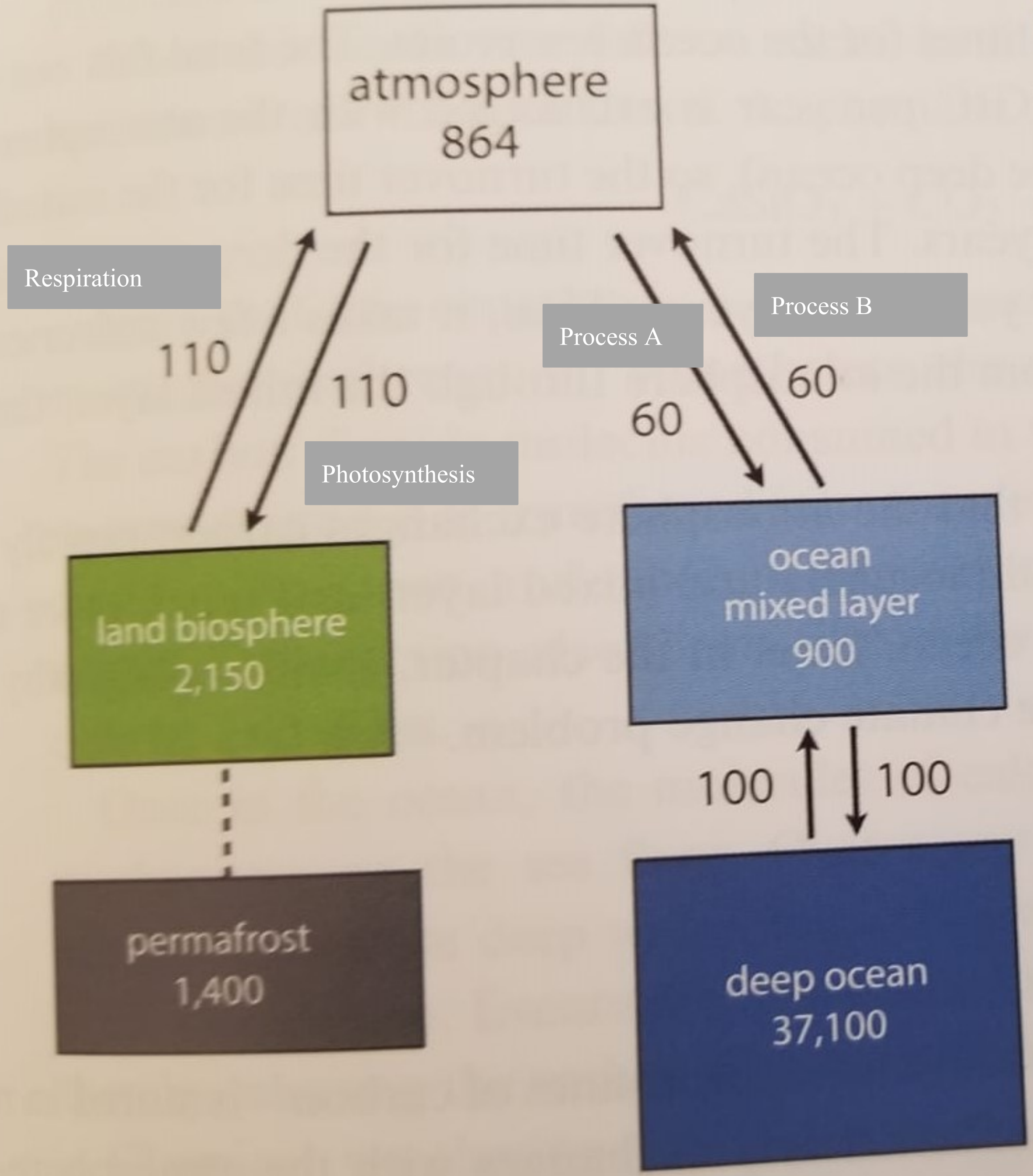


Figure 5.2 A schematic of exchange between the atmosphere, land biosphere, and ocean. Numbers in the boxes represent the amount of carbon stored in each reservoir, in GtC. Arrows represent fluxes, with values in GtC per year.

Approximate cycling times of the carbon molecule:

- Land biosphere: $\frac{2150}{110} = 20$ years
- Mixed layer of the ocean (upper 100 meters): $\frac{900}{160} = 5$ to 6 years
- Deep ocean (remaining deep parts of the ocean): $\frac{37100}{100} = 371$ years

Approximate cycling times of the carbon molecule:

- Atmosphere-land-ocean biosphere to/from the rock reservoir: $\frac{42414}{0.1} = 424{,}140$ years

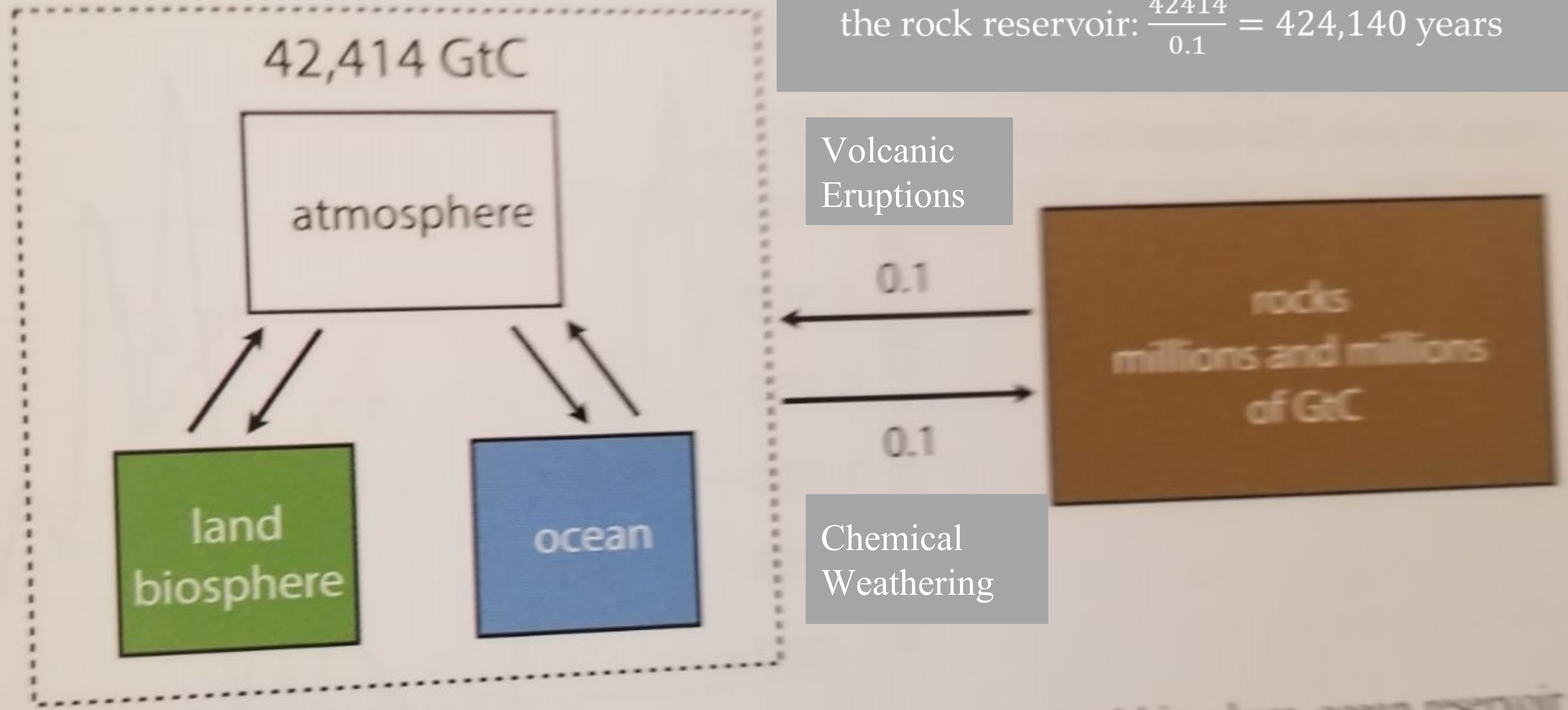
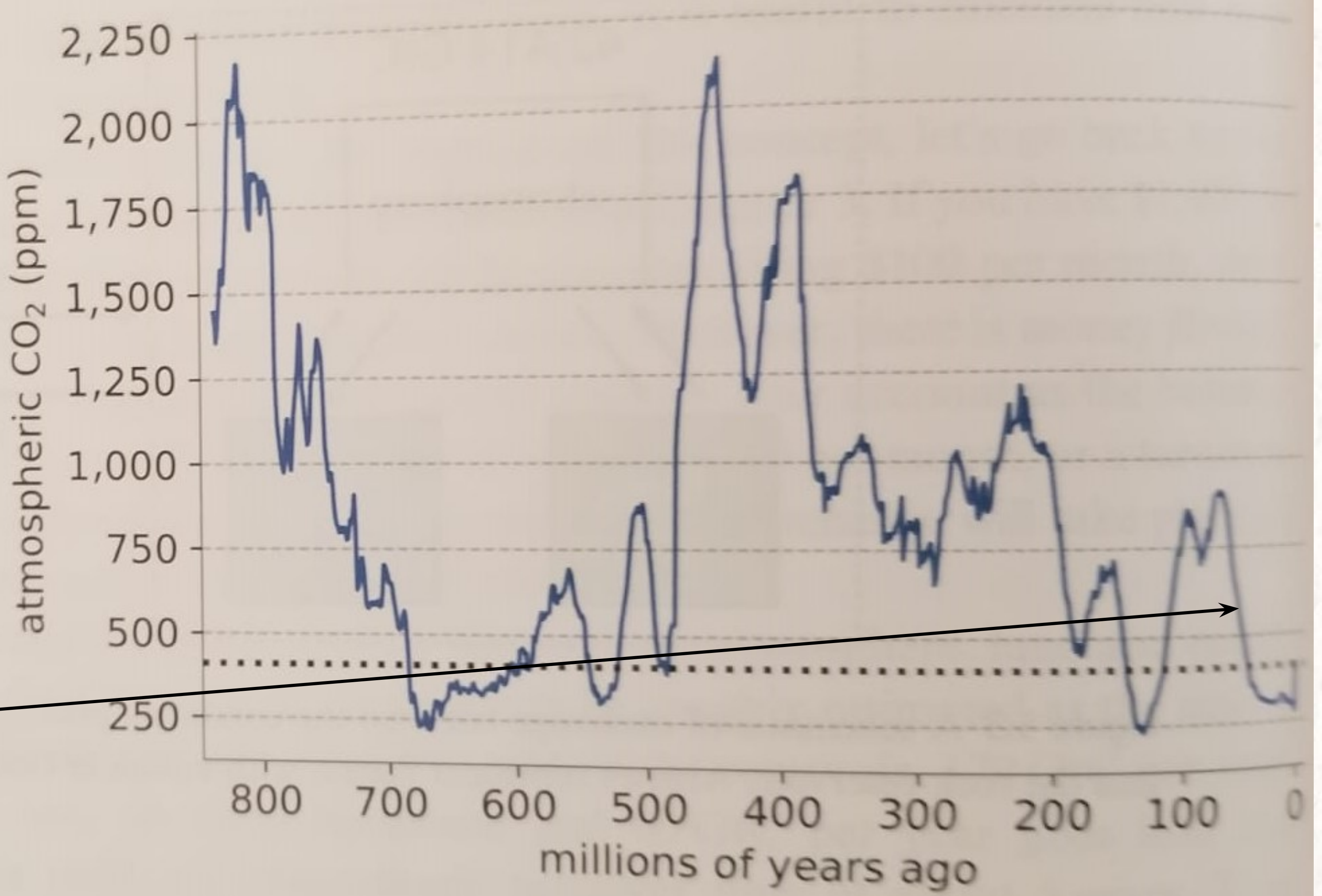


Figure 5.3 A schematic of exchange between the combined atmosphere–land biosphere–ocean reservoir and the rock reservoir. Arrows represent fluxes, with values in GtC per year.

Figure 5.4 Atmospheric carbon dioxide over the past 850 million years, in ppm. The dotted line is the atmospheric abundance in 2020, 410 ppm. Based on Figure 1 of Foster et al. (2017).



This decline in CO_2 level is coincident with the formation of Himalaya mountains. It is believed to have occurred when the Indian subcontinental plate collided with the Asian plate

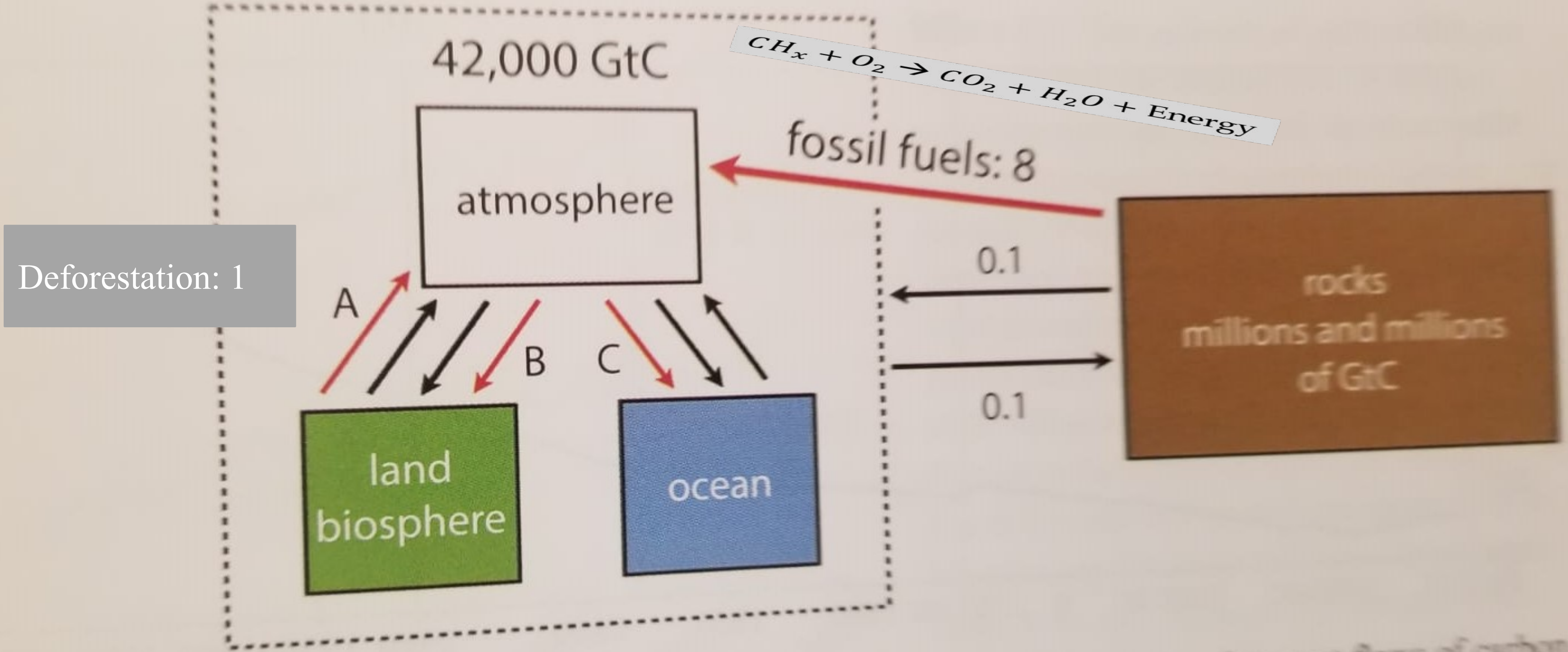


Figure 5.5 Diagram of the carbon cycle as perturbed by humans. Red arrows show net flows of carbon caused by human activities. Red arrows A, B, and C represent deforestation, enhanced absorption of carbon by the land biosphere, and enhanced absorption of carbon by the ocean, respectively.

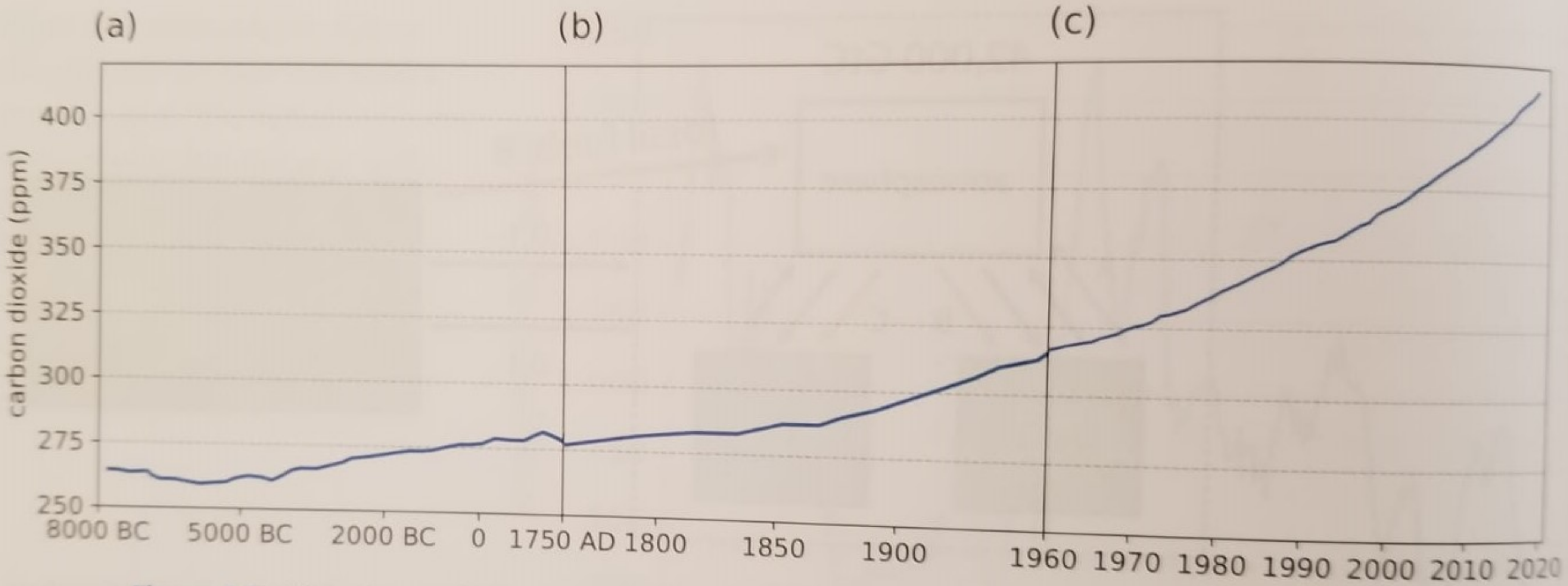


Figure 5.6 Abundance of annual-average carbon dioxide in our atmosphere (a) from 8000 BC to 1750 AD, (b) 1750–1960 AD, and (c) 1960–2020. Panels a and b are adapted from Figure SPM.1 of IPCC, 2007; data in panel c were measured at Mauna Loa, Hawaii by Dr. Pieter Tans, NOAA/GML and Dr. Ralph Keeling, Scripps Institution of Oceanography. Data downloaded from the NOAA Earth System Research Laboratory/Global Monitoring Division (www.esrl.noaa.gov/gmd/ccgg/trends/data.html, retrieved November 29, 2020).

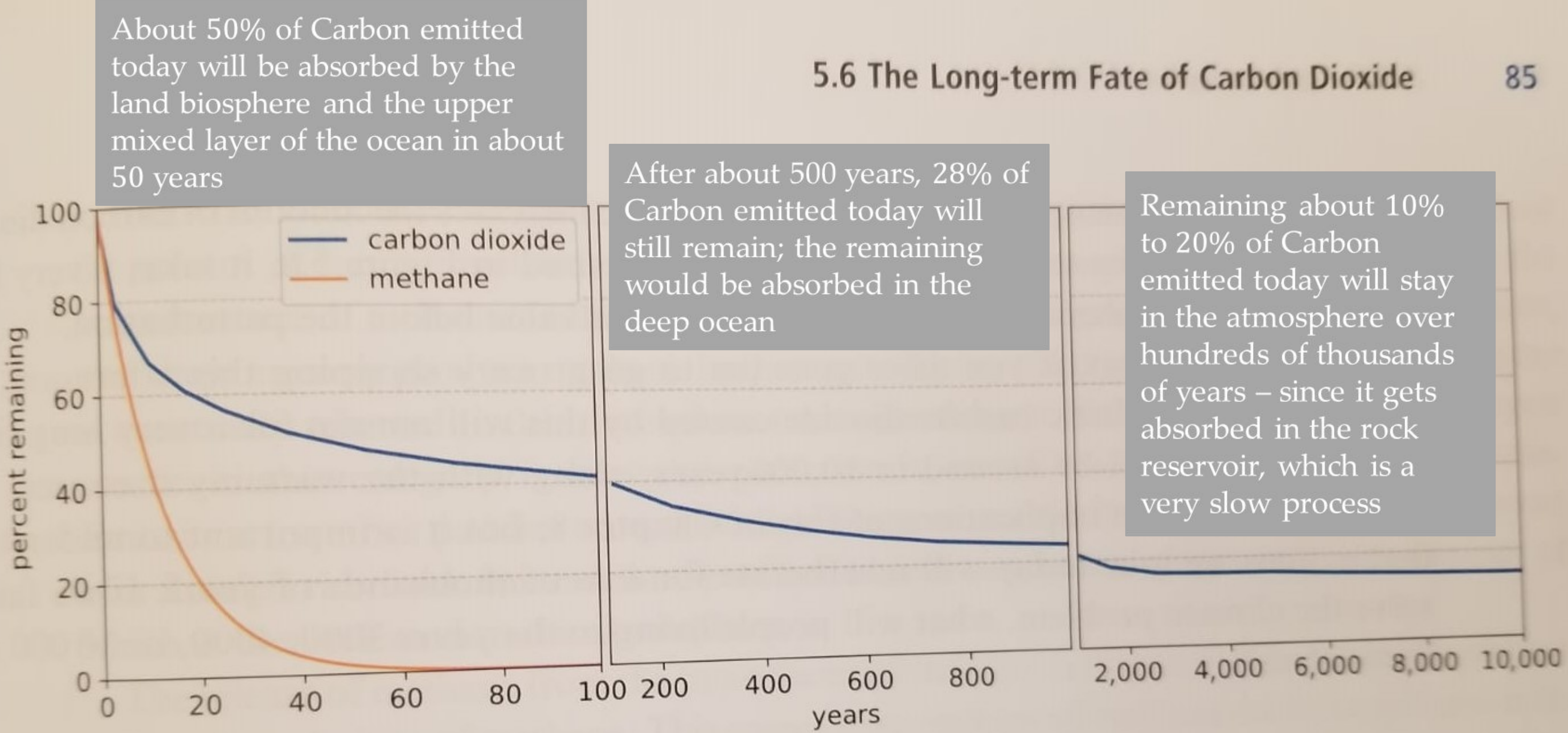


Figure 5.8 Fraction of carbon dioxide (blue) and methane (orange) remaining in the atmosphere after an initial pulse in year zero. The plot shows that it takes a very long time for carbon dioxide emitted to the atmosphere to be completely removed, whereas most of the methane is gone in a few decades. Carbon dioxide decay time is based on Figure 1 of Box 6.1 of Ciais et al. (2013). Methane decay time is based on an assumed lifetime of 12.4 years.

Delayed Effect of Greenhouse Gas Emissions

- Greenhouse gases act as a blanket on the Earth – they increase the effective number of layers n of the Earth, thereby drive the temperature of the Earth according to the formula

$$T = \sqrt[4]{\frac{S(1-\alpha)}{4\sigma} \times (n+1)}$$

- However, the effect of the greenhouse gas emission today is felt over hundreds of years and possibly more, since the temperature change due to today's emissions does not occur right away
- To see this, consider that a hypothetical planet without any atmosphere is receiving an energy $E_{in} = 238\ \mathrm{W}/m^2$ from the Sun
- Next, suppose that a single-layer of atmosphere is added to this planet. Let us consider the resultant effect

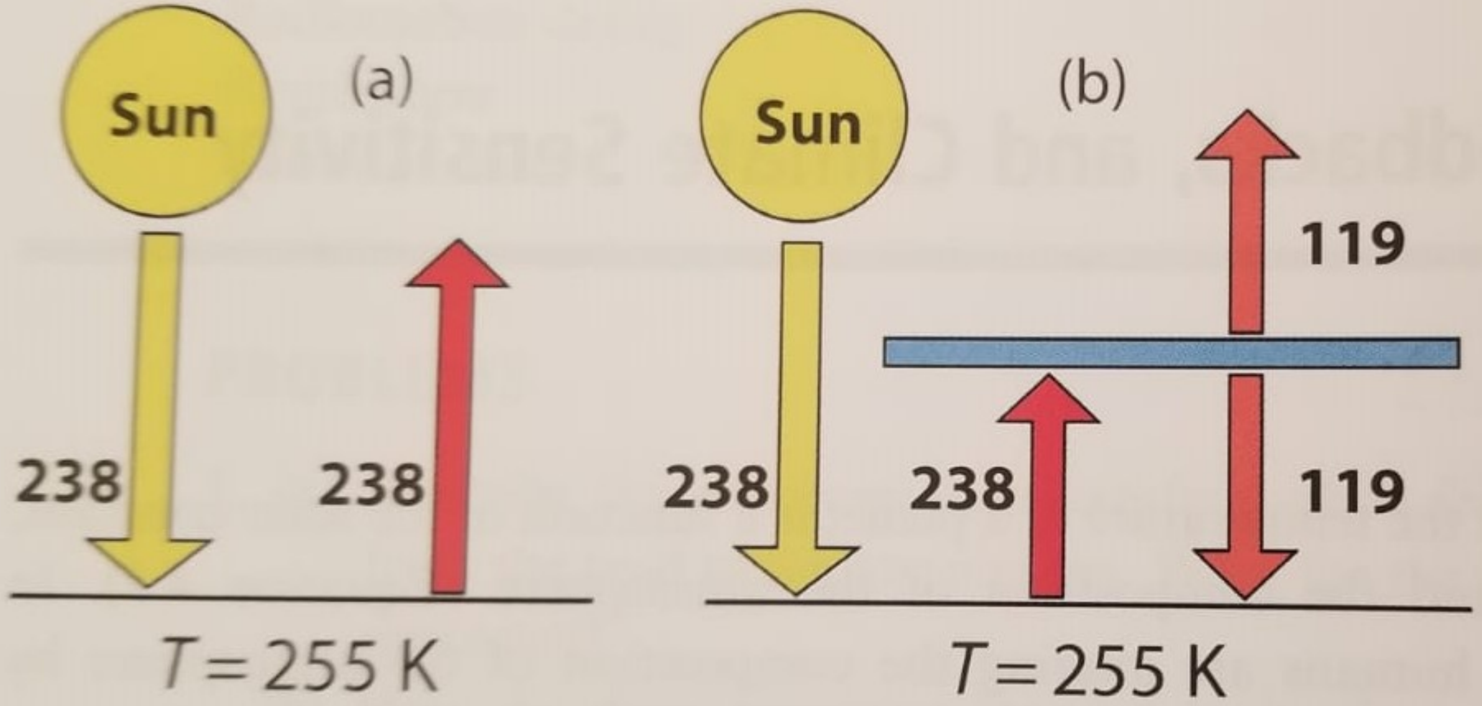


Figure 6.1 Schematic of energy fluxes on a planet (a) with no atmosphere, (b) the instant after a one-layer atmosphere is added to the planet

Radiative Forcing or RF

- Effectively, for the same $E_{in} = 238\ \mathrm{W}/m^2$, E_{out} in this case drops from 238 W/m^2 to 119 W/m^2 at the moment the atmosphere is added
- Radiative Forcing (RF) is defined as the change in $E_{in} - E_{out}$. Denote the delta change by the symbol Δ.
- $RF = \Delta(E_{in} - E_{out}) = \Delta E_{in} - \Delta E_{out}$
- The RF in the example on the previous slide:
- Suppose the Earth's Solar Constant S increases by 5%.
  - What is the resultant RF?
  - What will be the warming (the rise in the Earth's temperature) as a result?

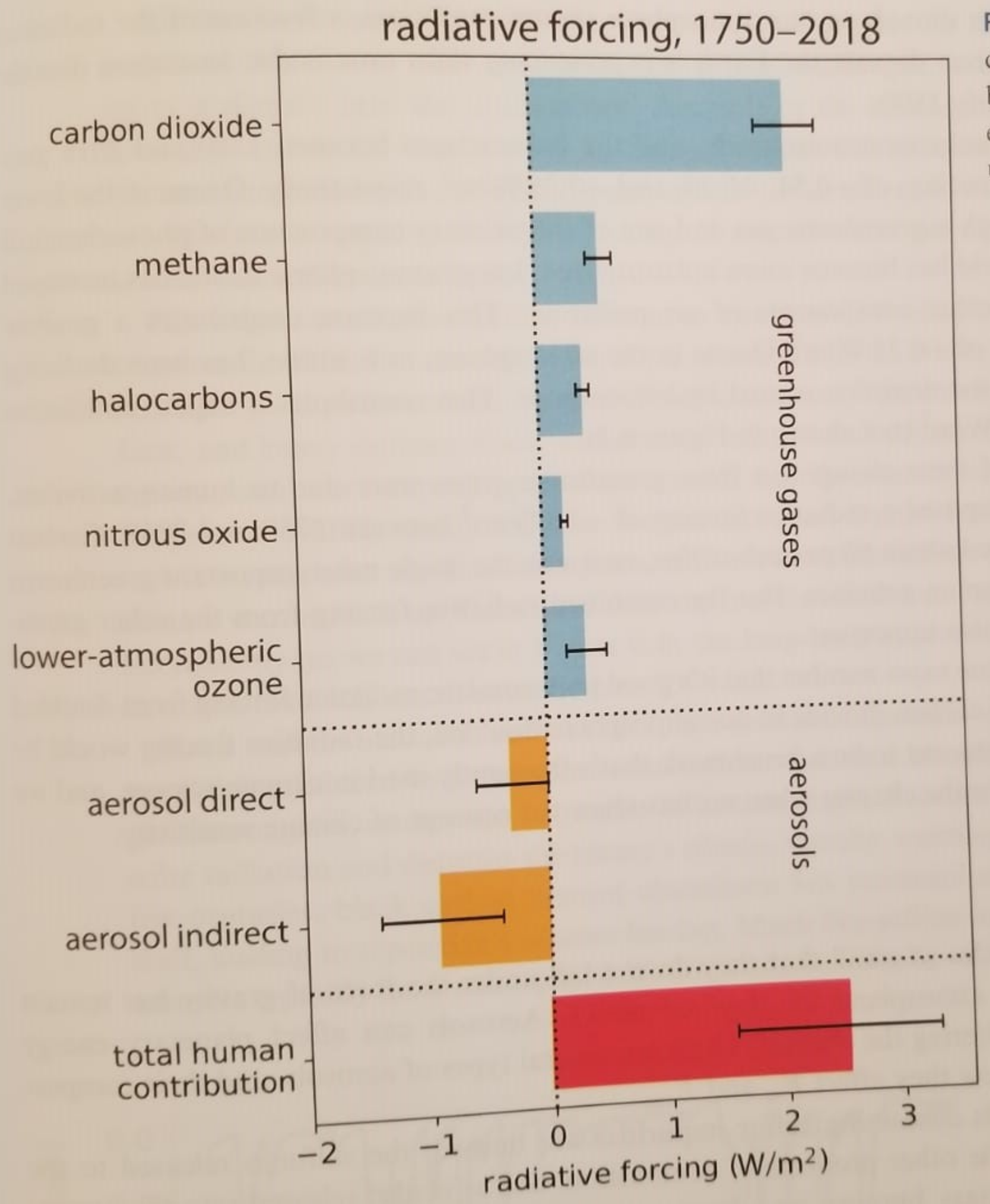


Figure 6.3 Radiative forcing caused by human activities between 1750 and 2018. The error bars indicate the uncertainty of the estimate.

Aerosol-Induced Negative Radioactive Forcing: Direct versus Indirect

- Direct Effect
  - Aerosols are small liquid droplets, often containing sulfur compounds
  - They have two markedly different life spans
    - A few weeks to months; these are generated
      - When the fossil fuels containing sulfur impurities are burnt
      - Due to biomass burning and from the natural processes in the oceans
      - Most of these aerosols exist in the troposphere (the lower atmosphere)
    - A few years
      - Volcanic eruptions, which go up to stratosphere, which is quieter and hence the life span of the aerosol increases
  - These aerosols reflect the incident solar rays and thereby increase the albedo. The net effect is that they exert a negative RF on the climate
- Indirect Effect
  - Aerosols act as cloud-condensation nuclei or CCNs – effectively the water droplets in the cloud
  - The number of CCNs increase in the cloud in the presence of the aerosols, which makes the cloud whiter, thereby increasing their reflectivity and in turn cooling the climate

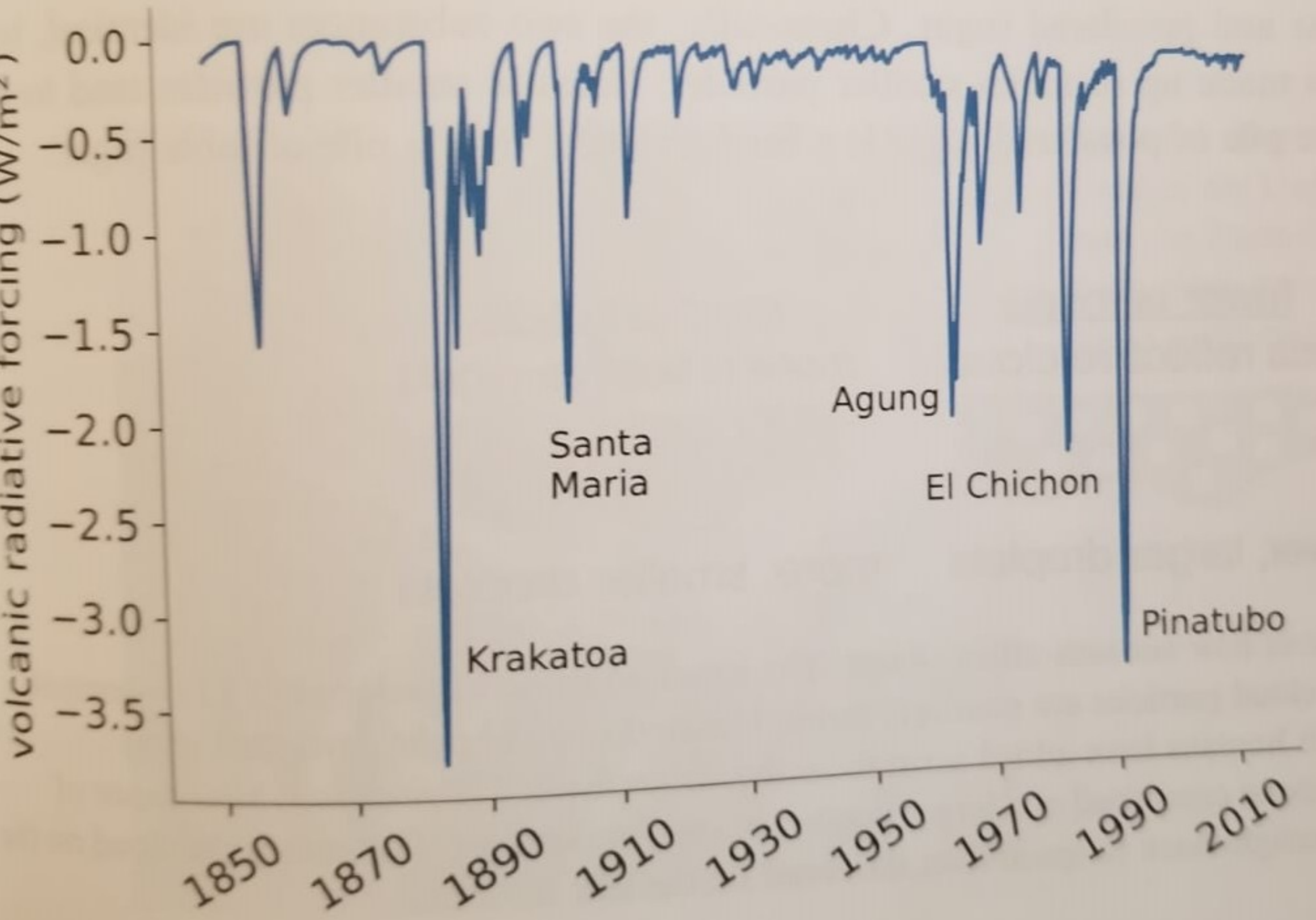
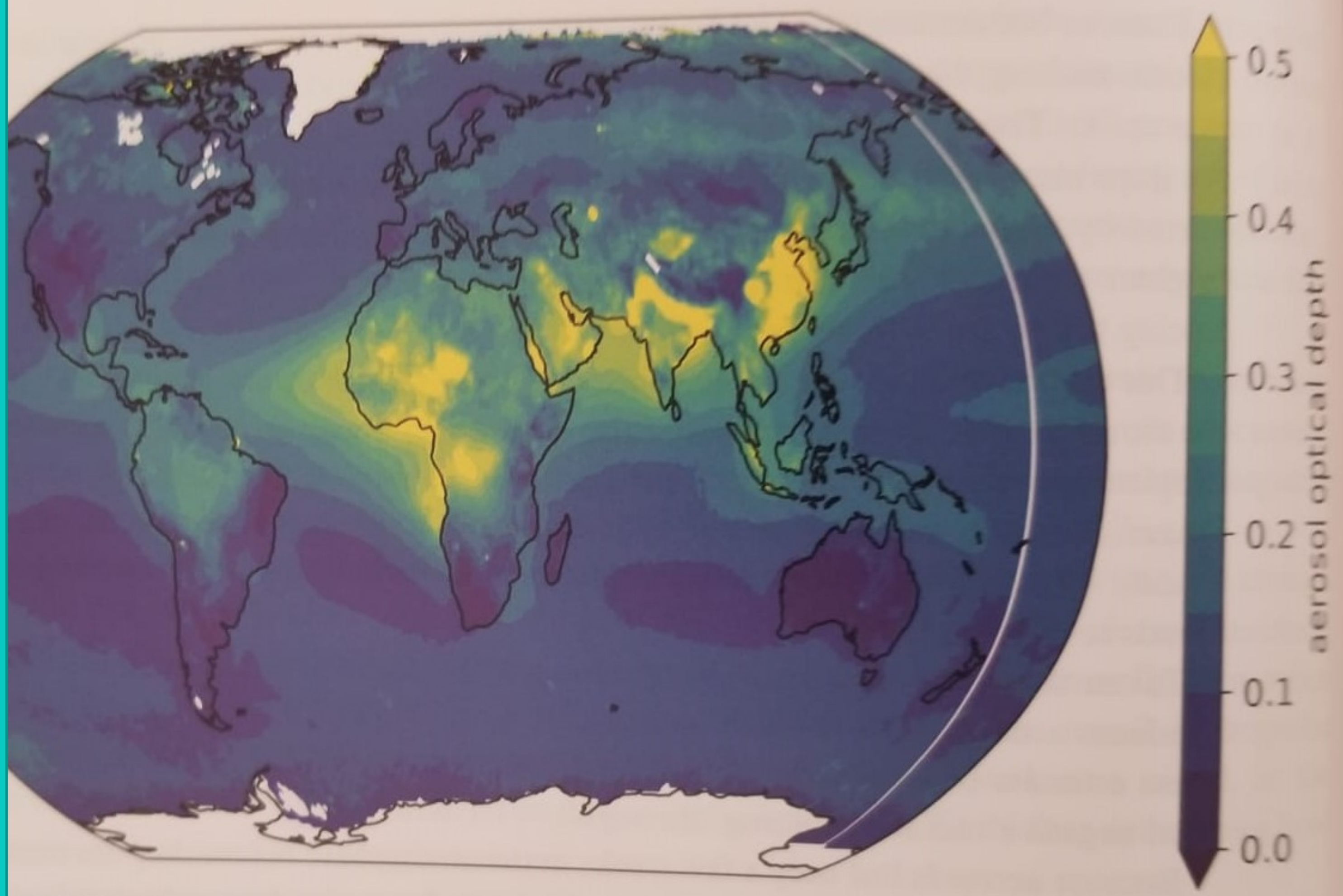


Figure 6.4 Radiative forcing (W/m^2) from volcanic aerosol. These estimates were obtained from NASA GISS; https://data.giss.nasa.gov/modelforce/strataer/, retrieved October 14, 2020.

- Higher concentration of aerosols is found in the developing countries where the air cleanliness laws are either not formulated or not enforced
- The aerosols have a beneficial effect on the global warming due to their negative RF
- However, the presence of the aerosols in the atmosphere is harmful to the health of the humans and so their abundance at a given location is detrimental to the human society at that location
- When the air quality laws take effect in the developing world, it will have an adverse effect on the global warming



6.7 Global map of annual average aerosol optical depth (a measure of the abundance of aerosols) e years 2005–2019. White areas denote regions where no data were obtained. Data are the MYD08 hly aerosol fields from the Moderate Resolution Imaging Spectroradiometer onboard NASA's satellite. This plot was produced on May 25, 2020, using the Giovanni online data system (https:// nni.gsfc.nasa.gov/giovanni/), developed and maintained by the NASA GES DISC.

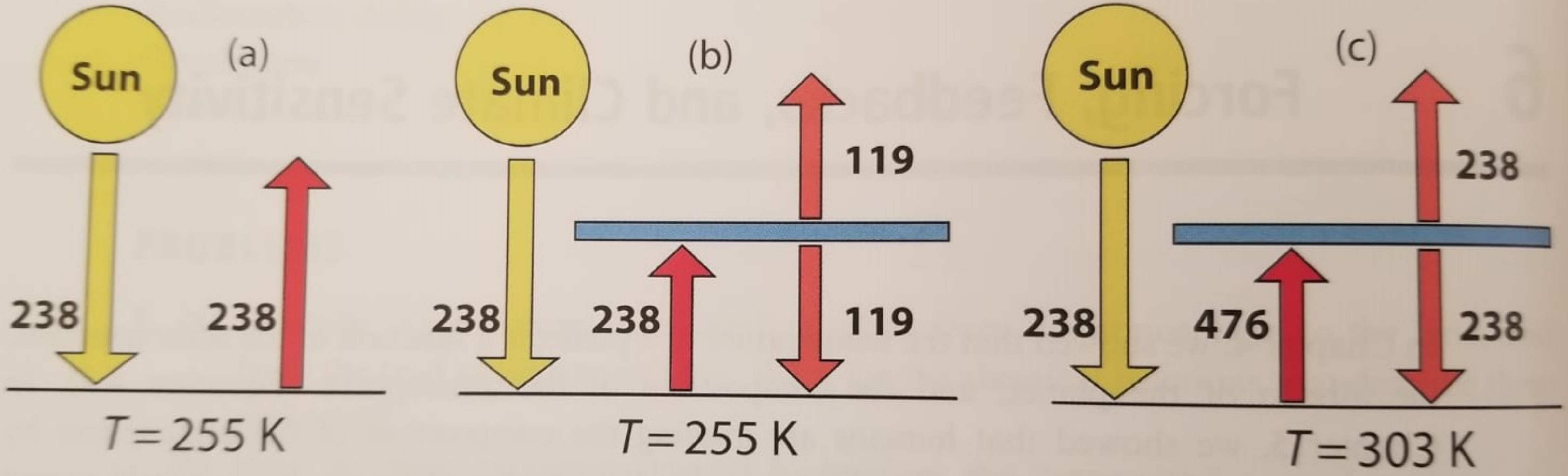


Figure 6.1 Schematic of energy fluxes on a planet (a) with no atmosphere, (b) the instant after a one-layer atmosphere is added to the planet, and (c) after the climate reaches its new equilibrium.

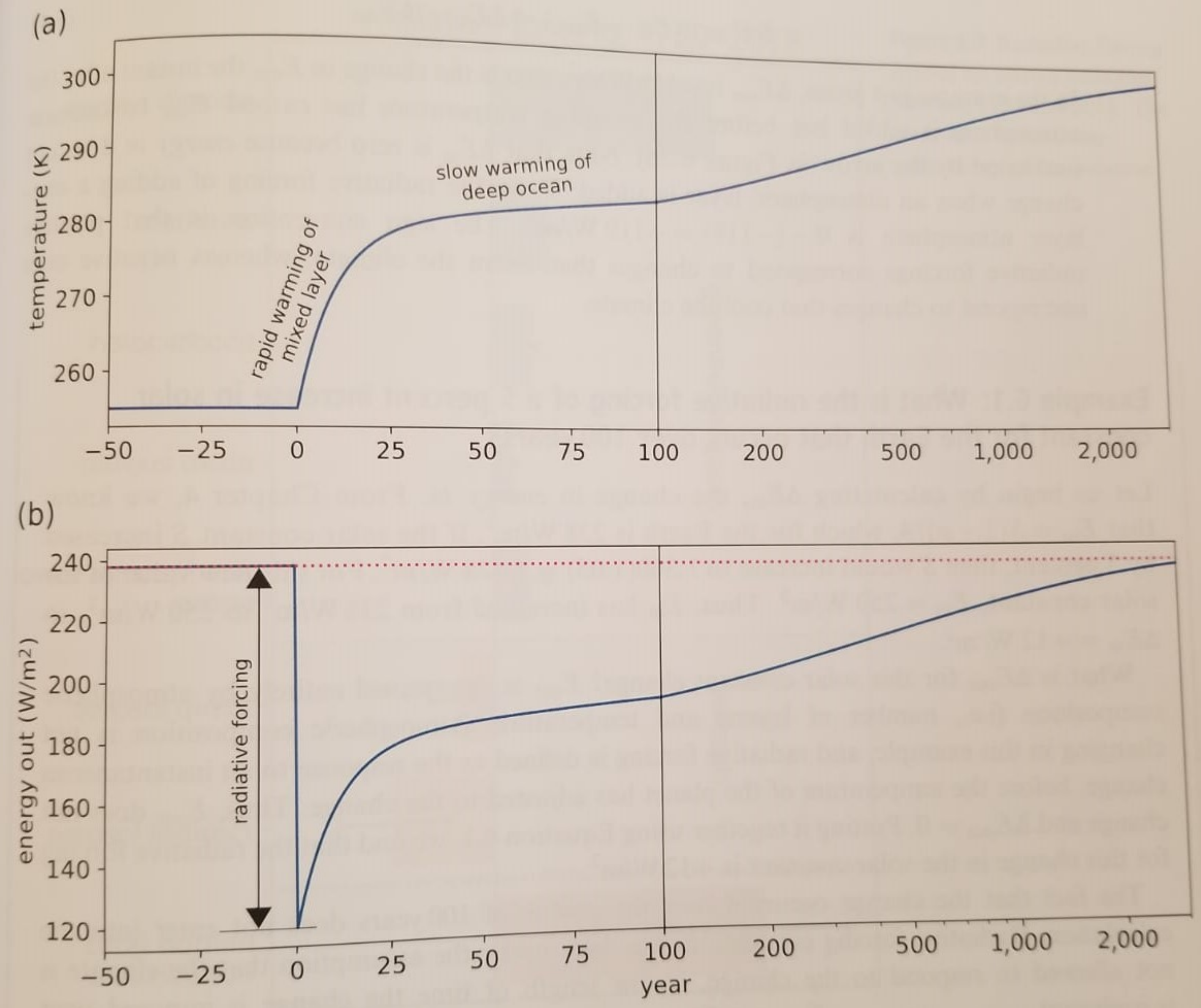


Figure 6.2 (a) Plot of temperature for the planet shown in Figure 6.1 as a function of time, (b) plot of *energy out* for the planet. A one-layer atmosphere is added instantaneously in year 0, and E_{in} for the planet remains constant at 238 W/m^2 (the dotted red line in panel b).

Net RF and Associated Global Warming

- The net RF due to human activities over the years 1750 to 2018 is +2.5 W/m^2
- Due to this forcing, the Earth's energy output has increased and its temperature has climbed
- Measurements of the Earth's energy balance show that E_{in} exceeds E_{out} today by 0.8 W/m^2
- Thus, our Earth has warmed by that much over the past 268 years to erase 1.7 W/m^2 of the radiative forcing
- The Earth will continue to heat up to erase the remaining $0.8\frac{W}{m^2}$ of RF. This is a warming that we are committed to and cannot stop from happening

Temperature Increase due to Increased RF

- Let us say that the net RF increases by 1 W/m^2 from its current value of 238 W/m^2
- Recall that we determine the temperature using Stefan-Boltzmann Law

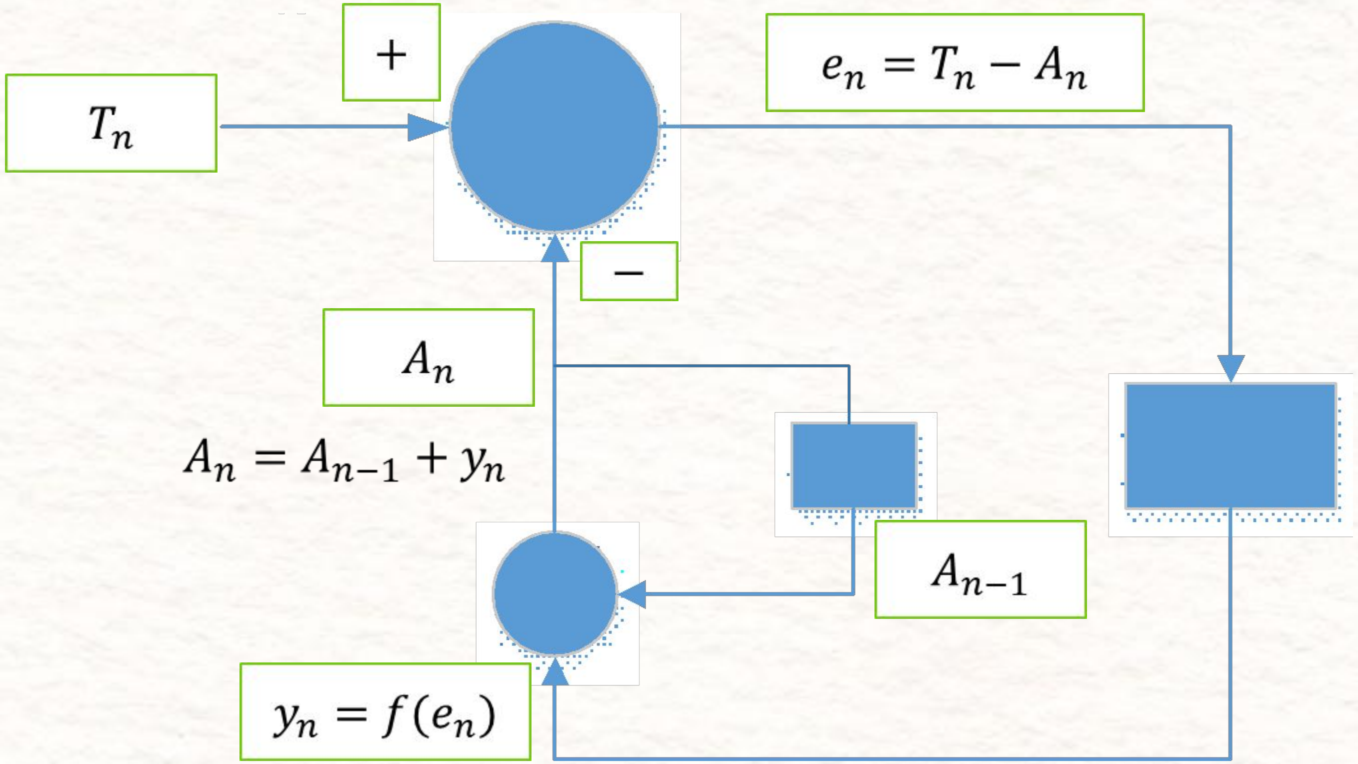
Eout	sigma	T
238	5.67E-08	254.5356
239	5.67E-08	254.8025
		0.266949

- Thus, the temperature increase equals $\approx \frac{0.25^o K}{1 \frac{W}{m^2}\, change\ in\ RF}$
- If CO_2 doubles, it imposes an RF of $4 \frac{W}{m^2}$. This would lead to a temperature increase of $1^o K$
  - This is a rule of thumb in the climate science: the Earth's climate sensitivity is $1^o K$ for doubled carbon dioxide
  - Detailed computer simulations confirm this analysis and predict a temperature change of 1.2^oK for the doubling of CO_2 levels in the Earth's atmosphere

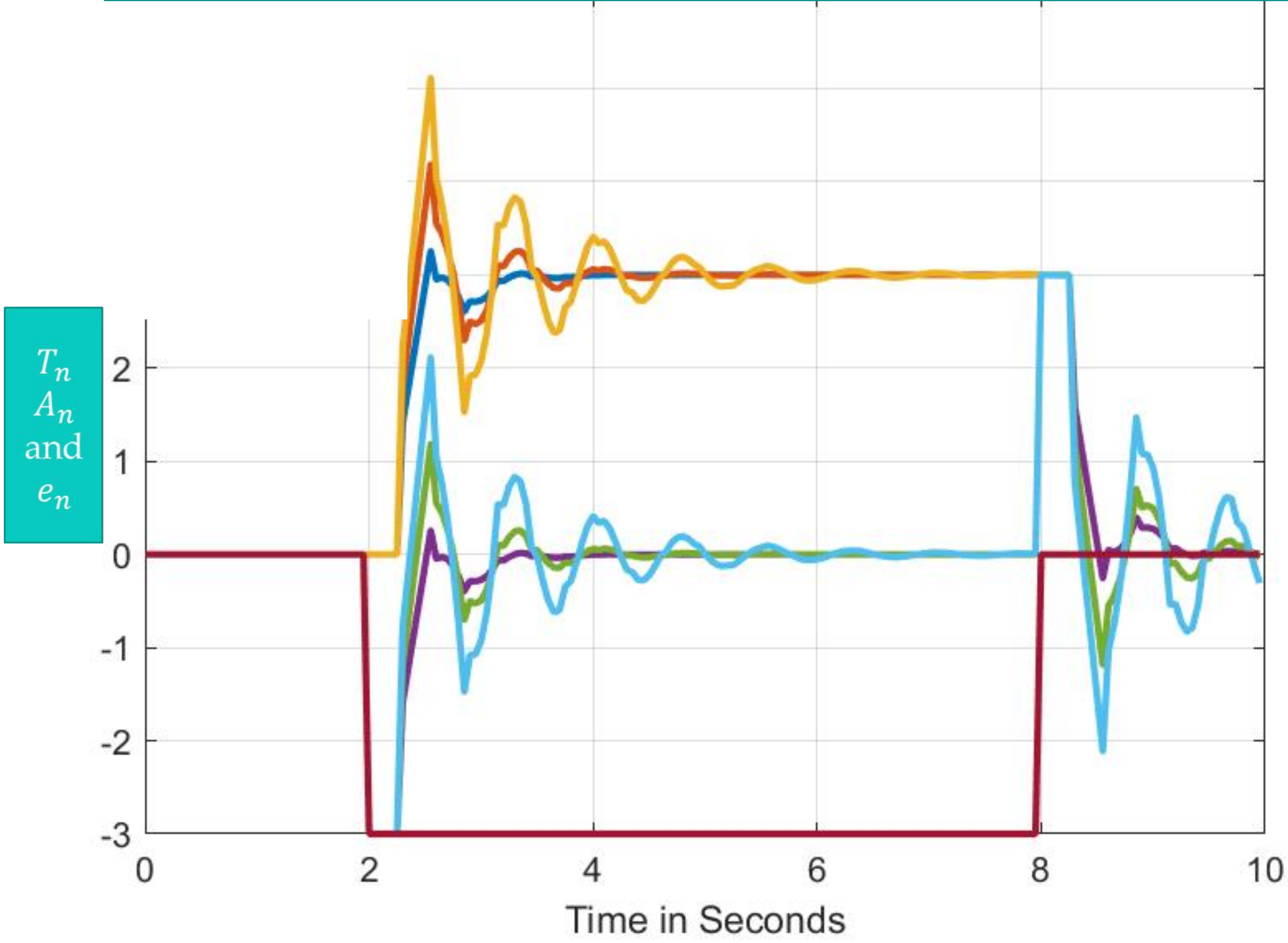
Feedback Loops in the Earth's Climate

- Feedback control systems are everywhere
  - Brain receives feedback from your eyes and the pressure differential in your ears to stand upright and walk without losing balance; a big part of Robot design involves the feedback control
  - Smart homes embedded with Internet of Things and Sensors and Actuators have feedback control loops that fine tune the temperature inside the house, the security systems, the kitchen appliances, etc.
  - Chemical plants and factories in general have feedback control systems that ensure that the chemical processes operate at the target settings and that extreme runaway processes do not occur
  - Even human behavioral patterns often exhibit feedback and control
- Block Diagram of a Feedback Loop, Notations:
  - n: Iteration index
  - T_n: Target value of a parameter at iteration n
  - A_n: Actual value of the parameter at iteration n
  - $e_n = T_n - A_n$: the error at iteration n
  - D: denotes a delay operator (think of it as a memory register, which stores the prior value)

Block Diagram of a Simple Feedback Loop

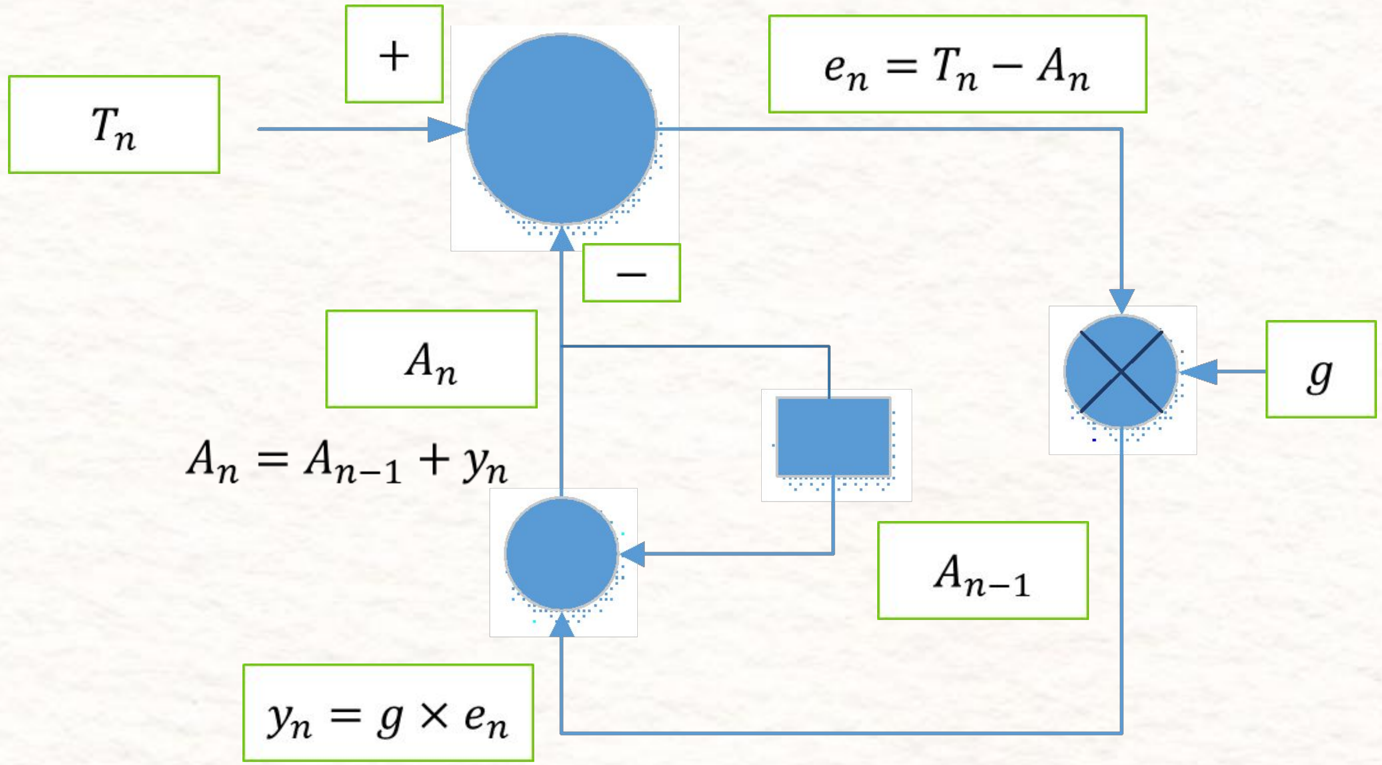


An Example of Negative Feedback with Three Different Types of Filters



Feedback Loop 1: Filter is Replaced by a Multiplier

- A simple scheme in which the filter is replaced by a multiplier g

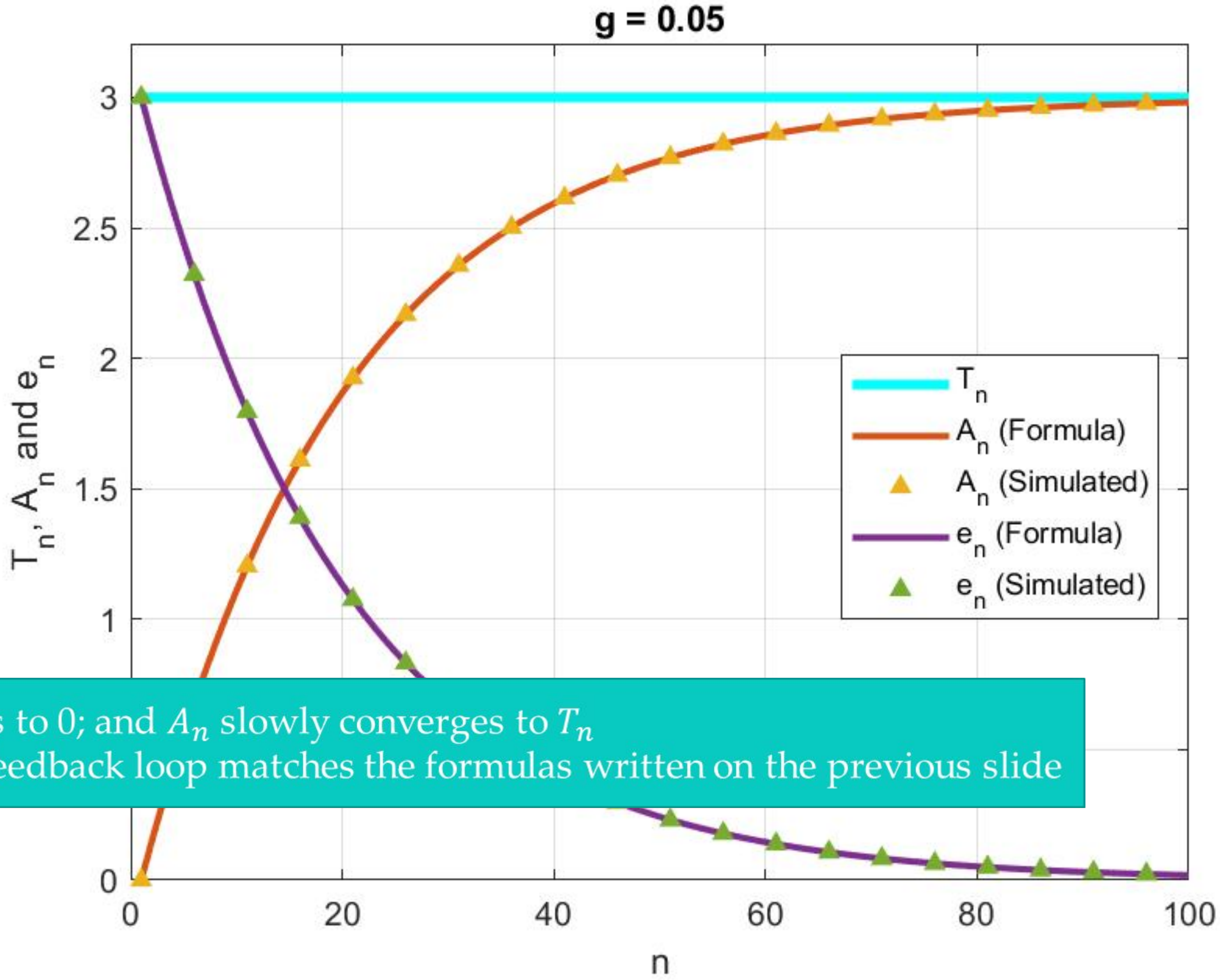


Equations of Feedback Loop 1

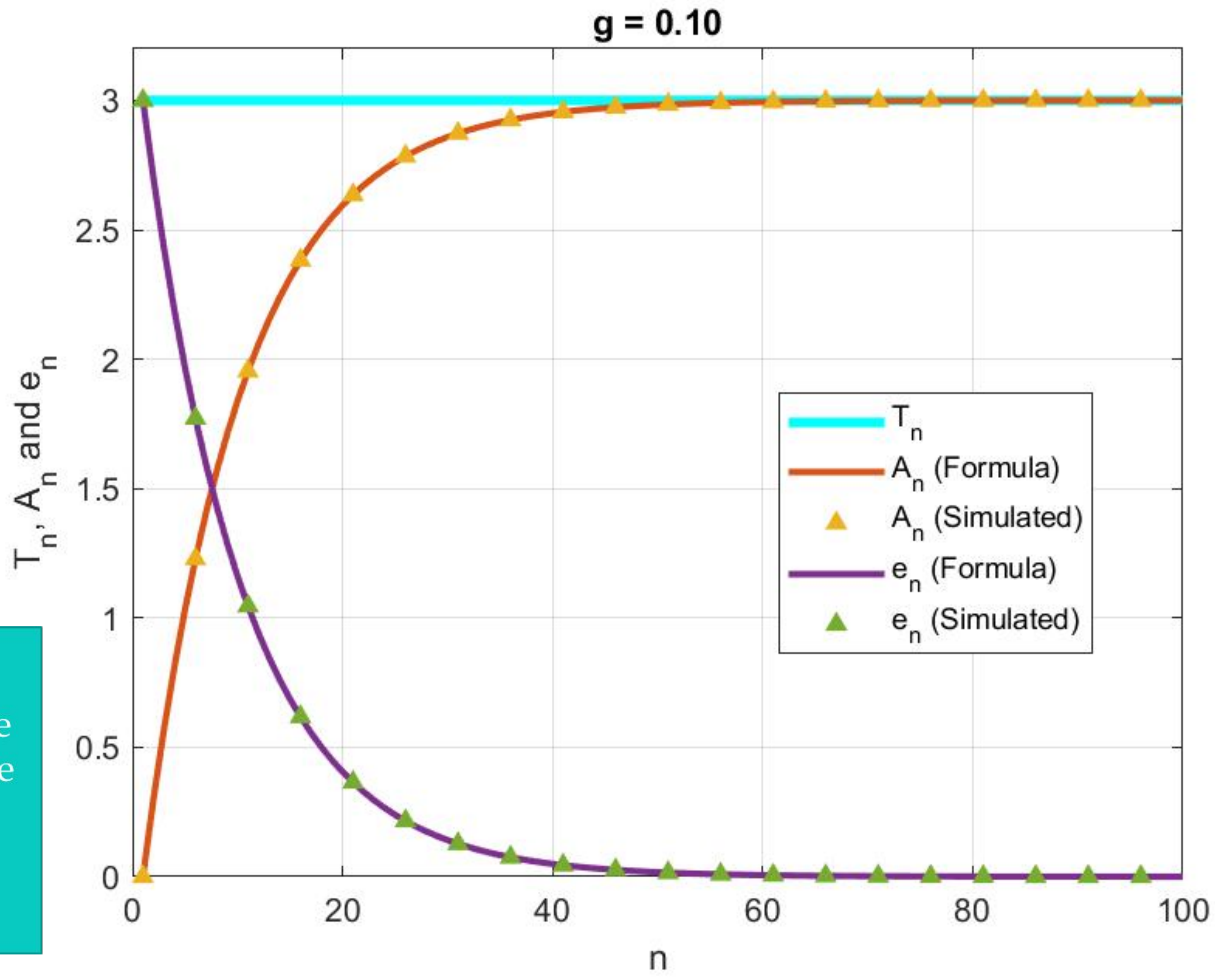
- The equations of different parameters of the feedback loop 1 on the previous slide are written below for $n = 0, 1$, and 2
  - Here, the assumption is that the target parameter $T_n = T$ for all n, and $A_{n=0} = 0$
  - Also, we have denoted $1 - g$ as G
- <u>**Question:**</u> generalize the equations that are written for the first few values of n and derive the equations for $A_{n=N}$ and $e_{n=N}$ as a function of arbitrary loop index $n = N$ which are highlighted in the red below

0					
1					
2					

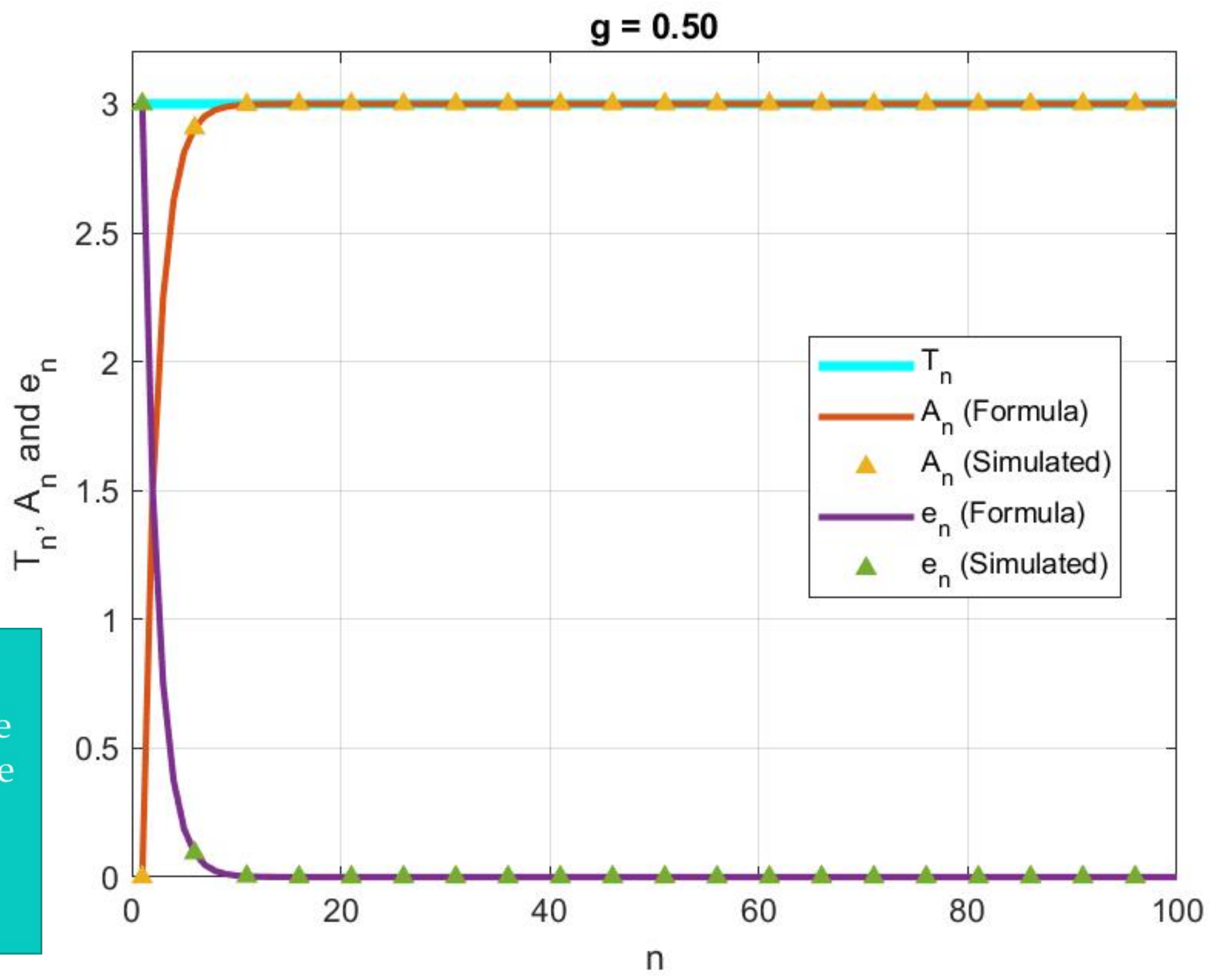
Feedback Loop 1



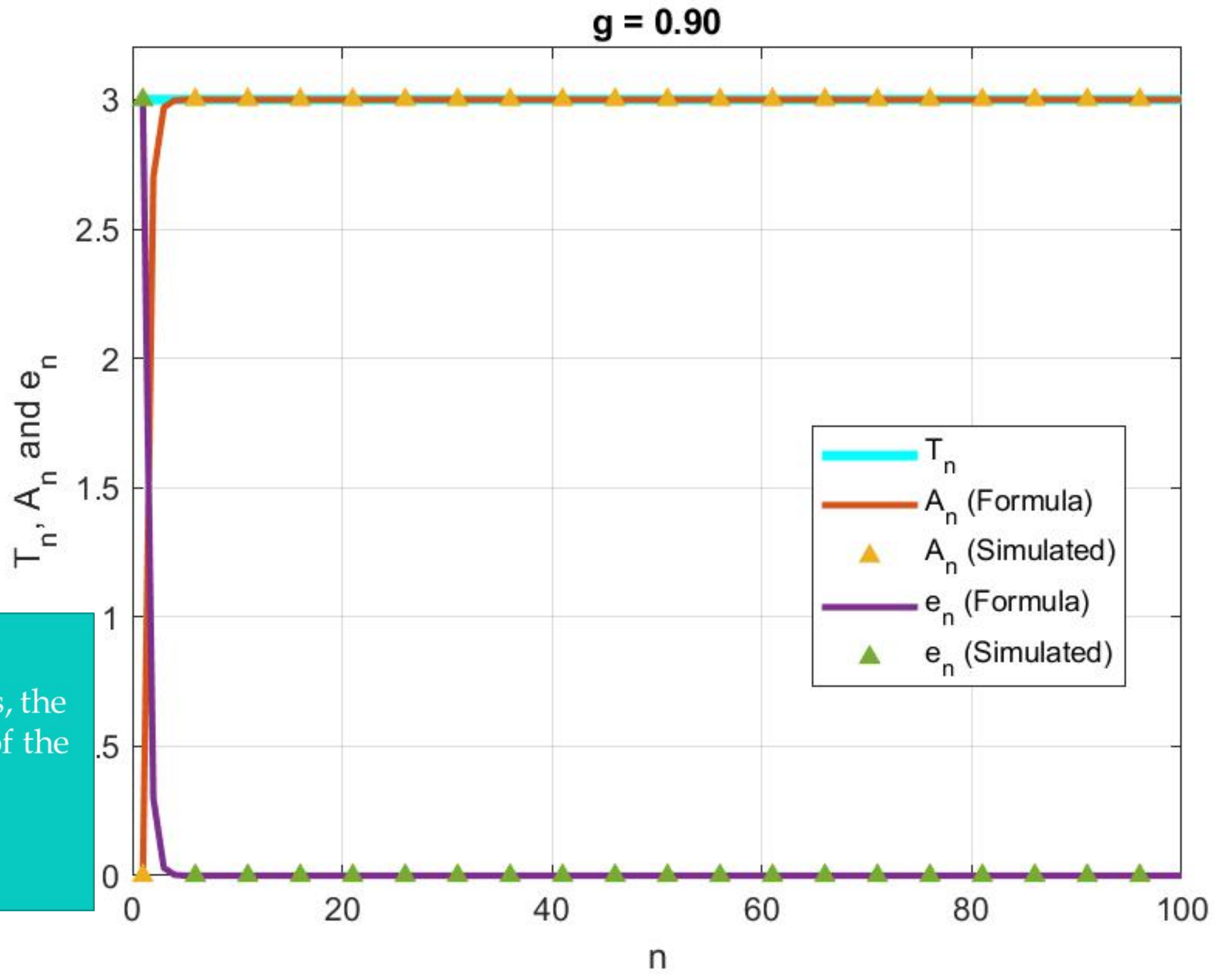
- e_n slowly converges to 0; and A_n slowly converges to T_n
- Simulation of this feedback loop matches the formulas written on the previous slide



- As g increases, the convergence of the feedback loop speeds up



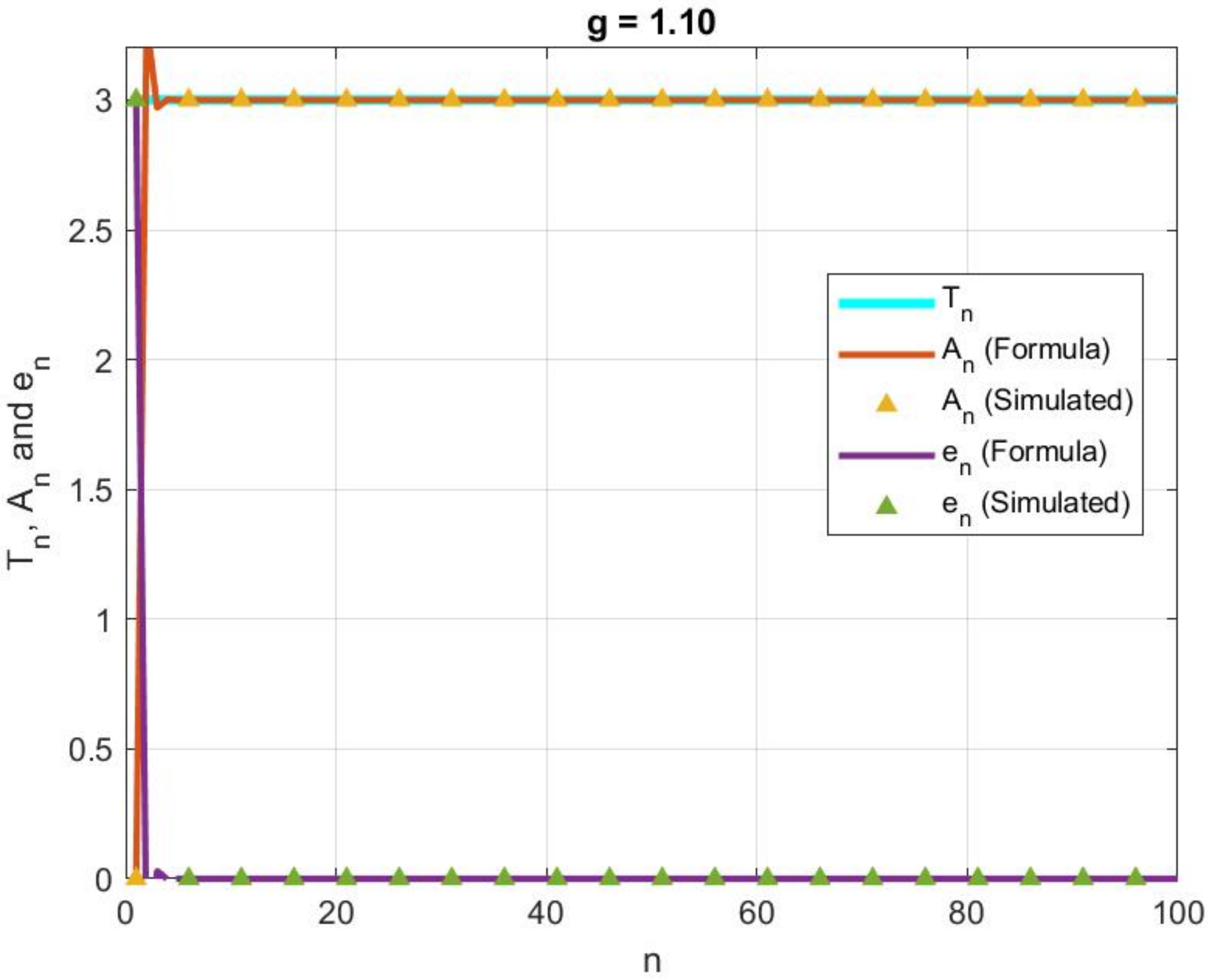
- As g increases, the convergence of the feedback loop speeds up



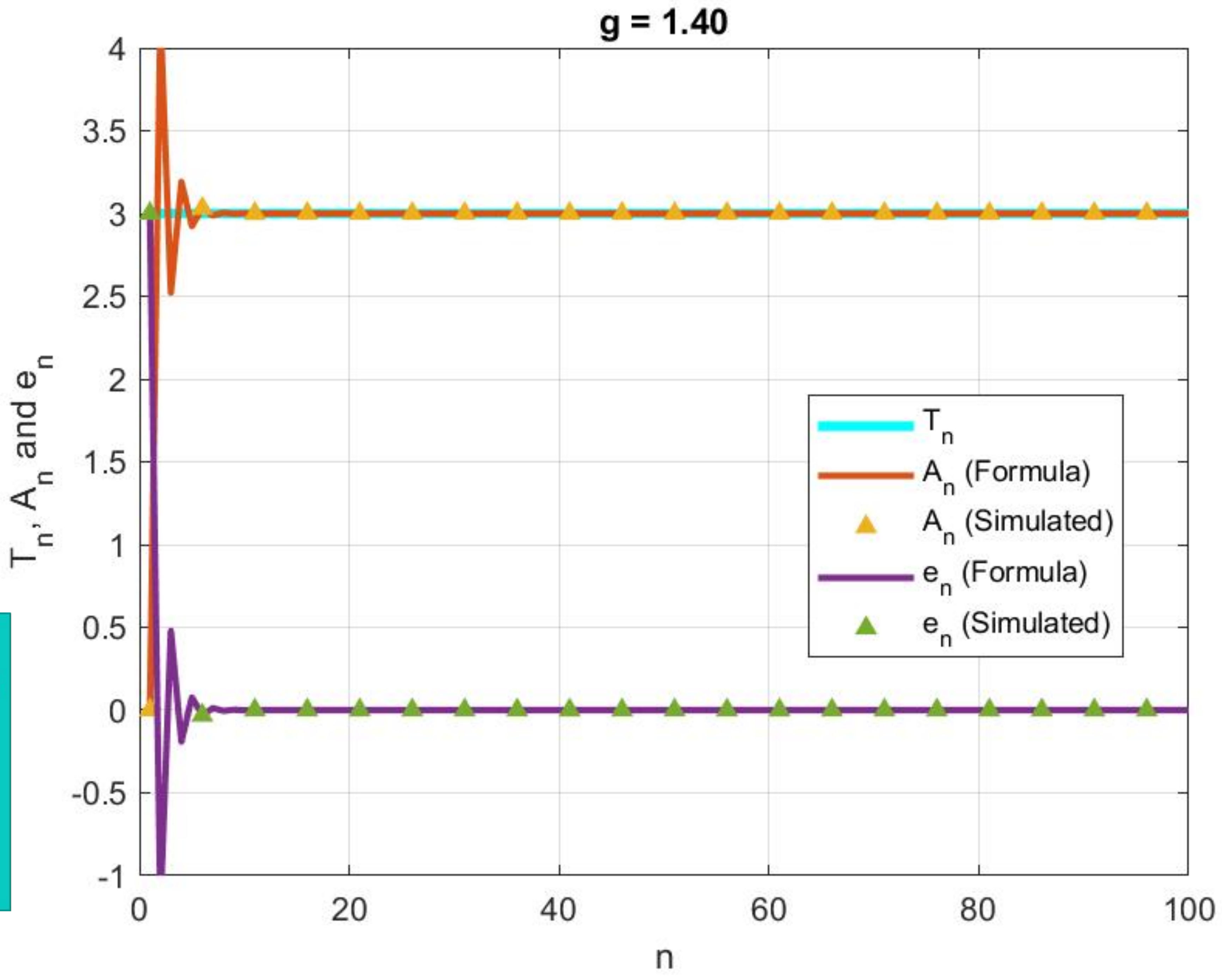
- As g increases, the convergence of the feedback loop speeds up

Questions

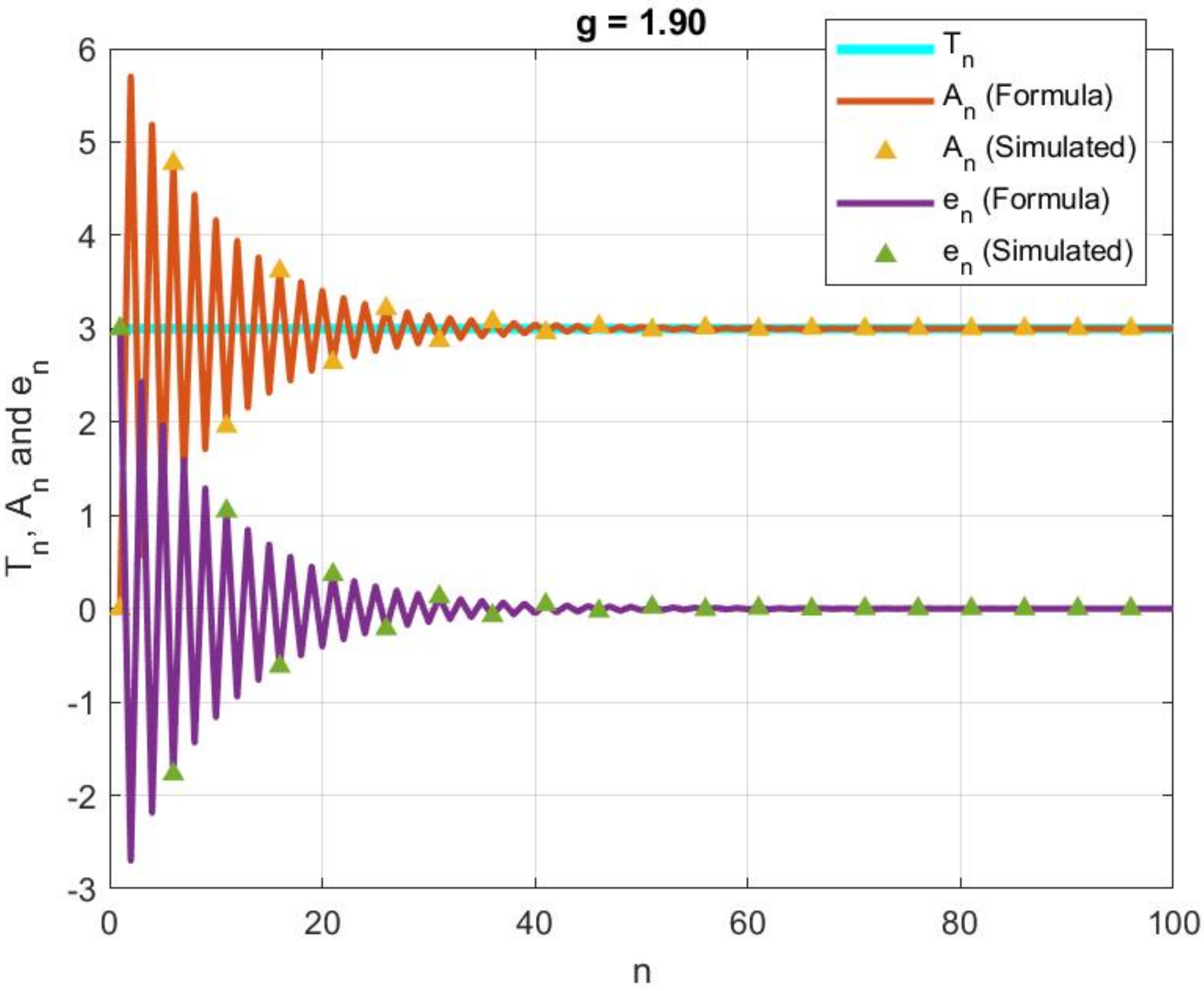
- What is the expected loop behavior for
  - $g = 0$?
  - $g = 1$?
  - $1 < g \leq 2$?
  - $g > 2$?



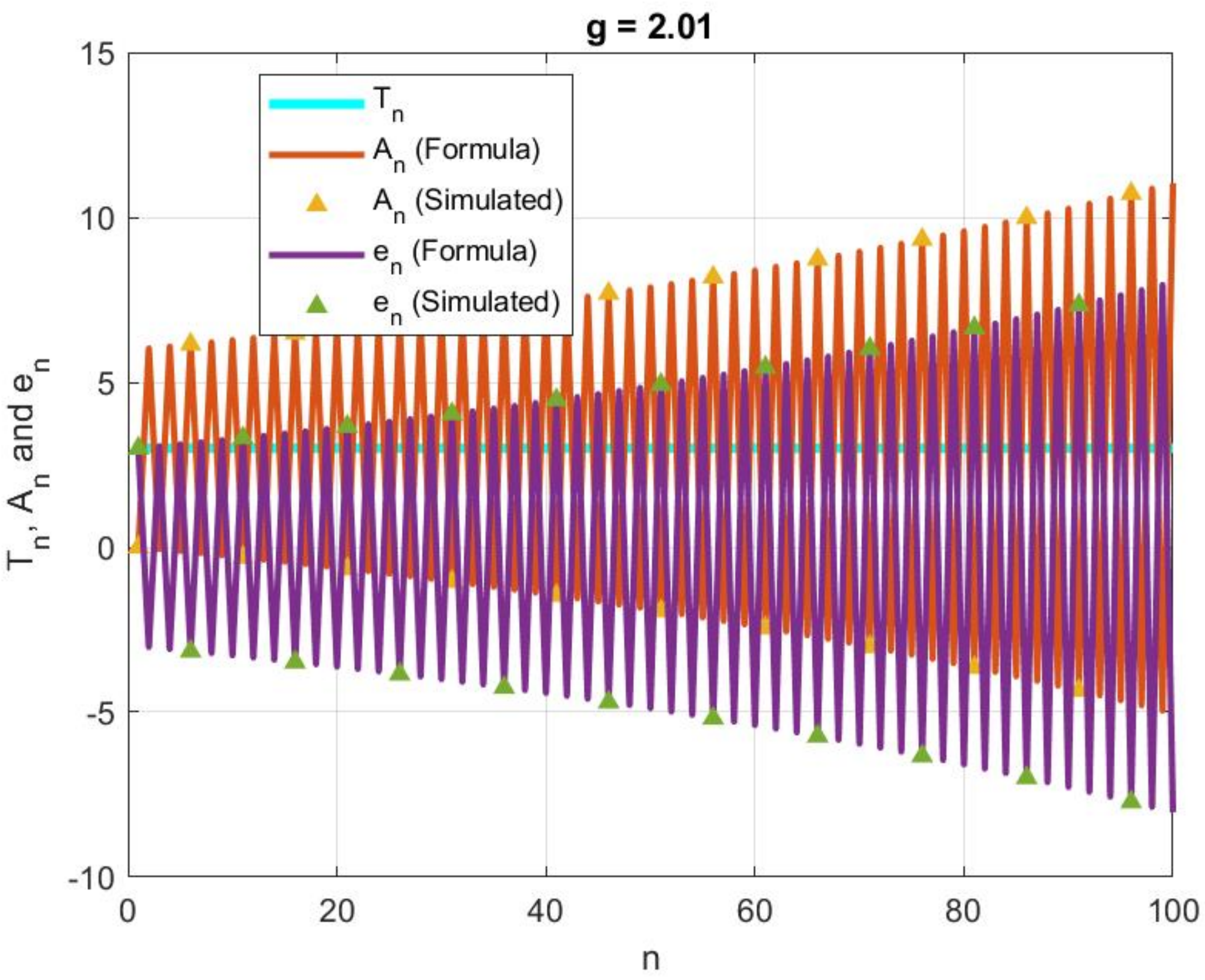
- Some ringing is observed when g exceeds unity



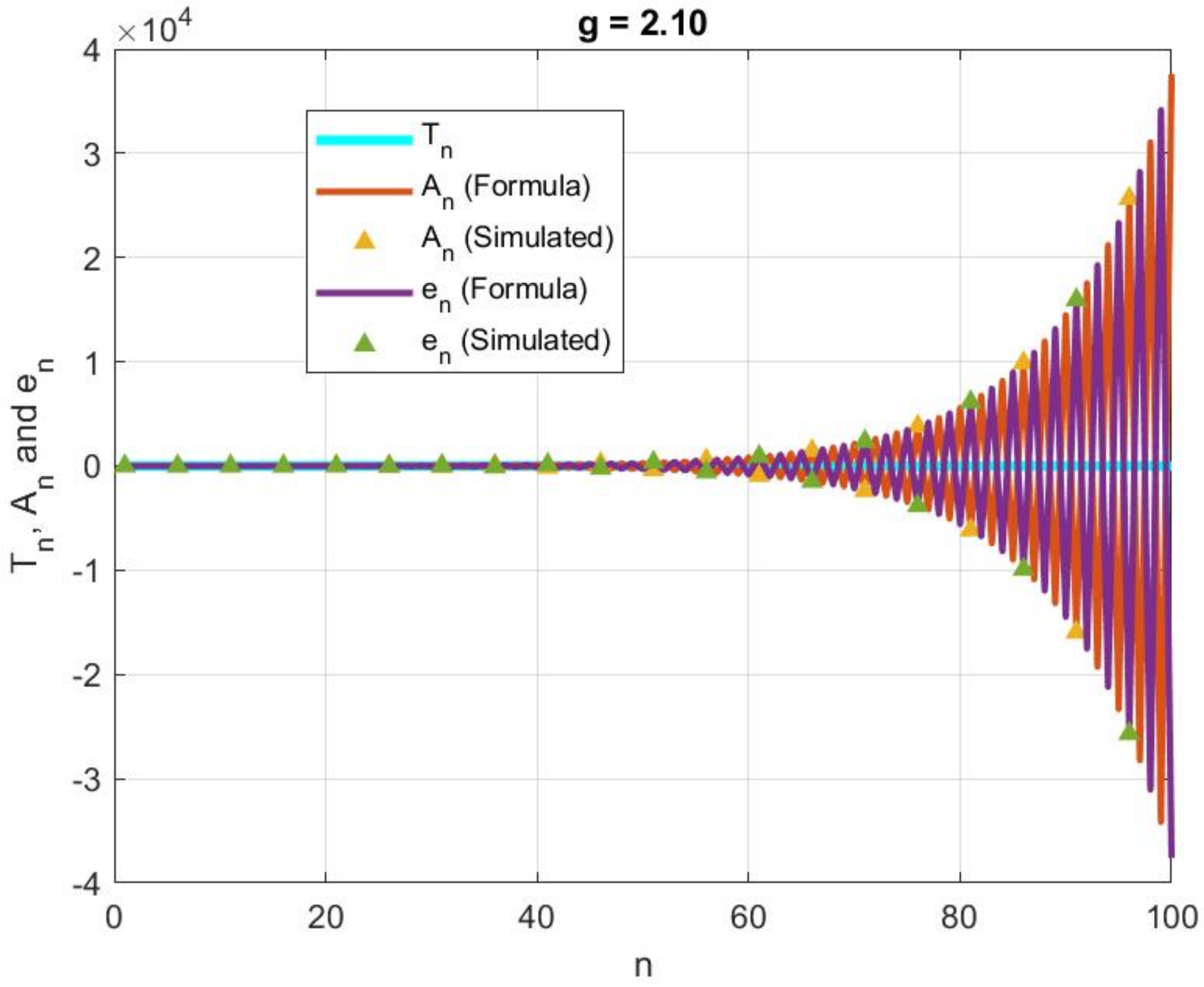
- Some ringing is observed when g exceeds unity



- Some ringing is observed when g exceeds unity



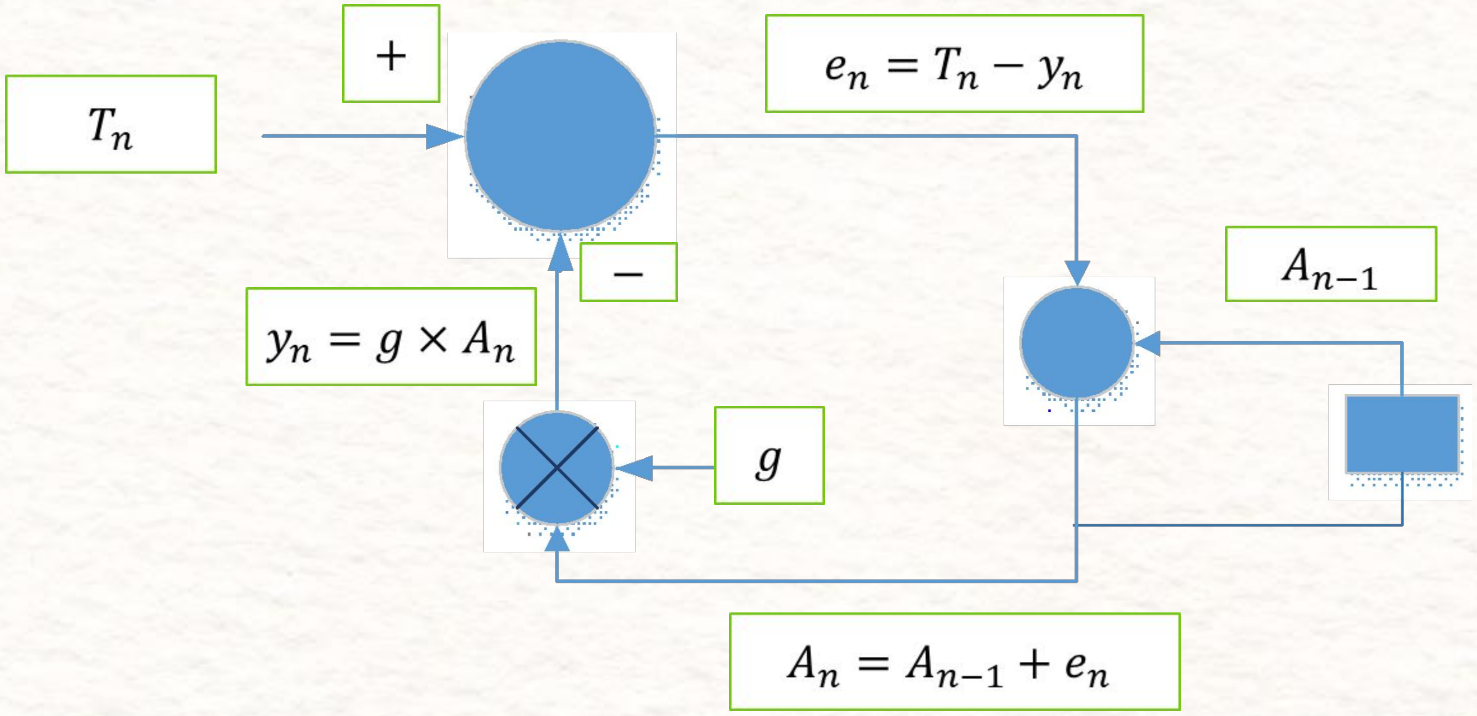
- When g exceeds 2, i.e, $G > 1$, the loop does not converge



- When g exceeds 2, i.e, $G > 1$, the loop blows up

Feedback Loop 2: the Multiplier Location is Changed

- A simple scheme in which the filter is replaced by a multiplier g and the location of the multiplier is shifted

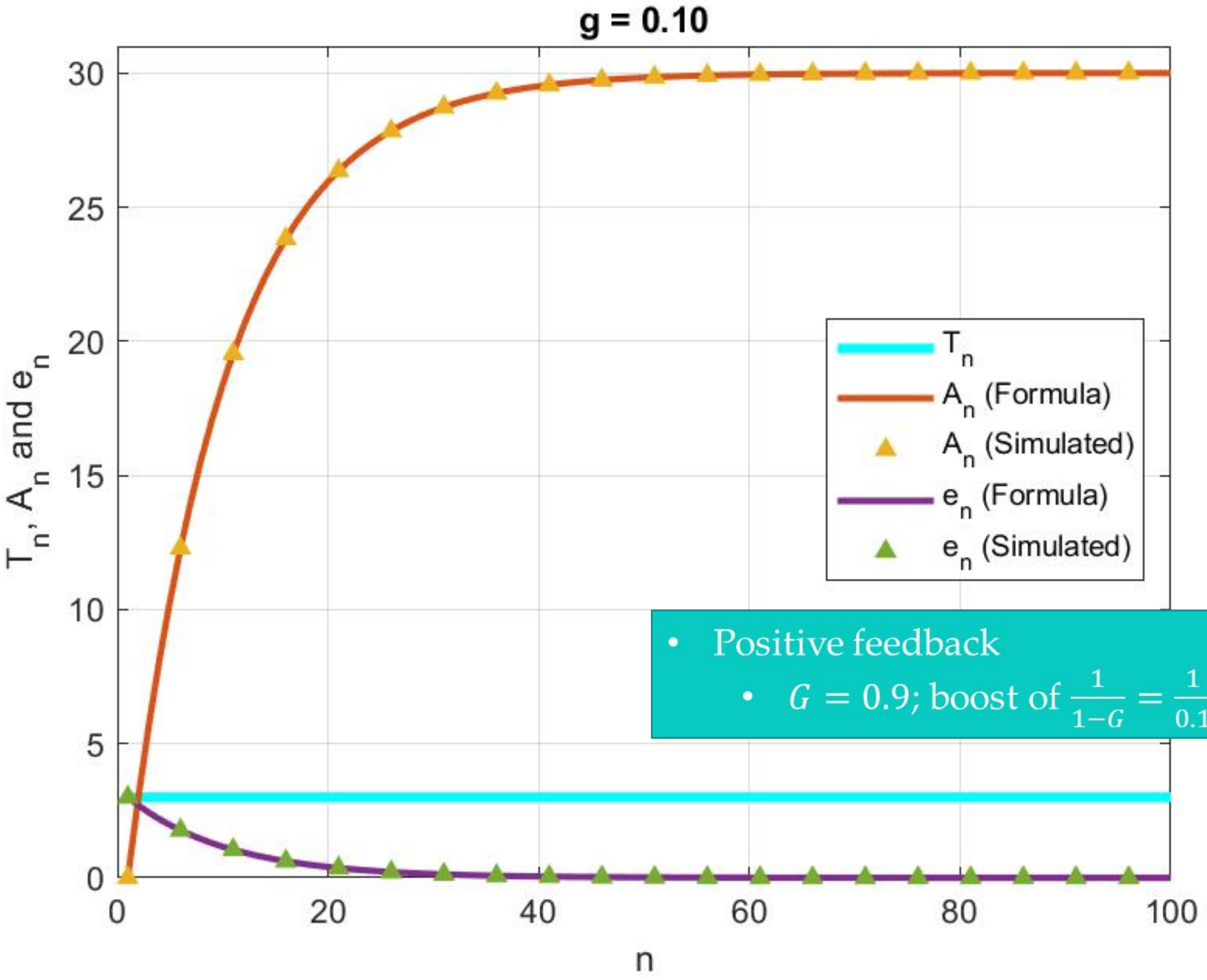


Equations of Feedback Loop 2

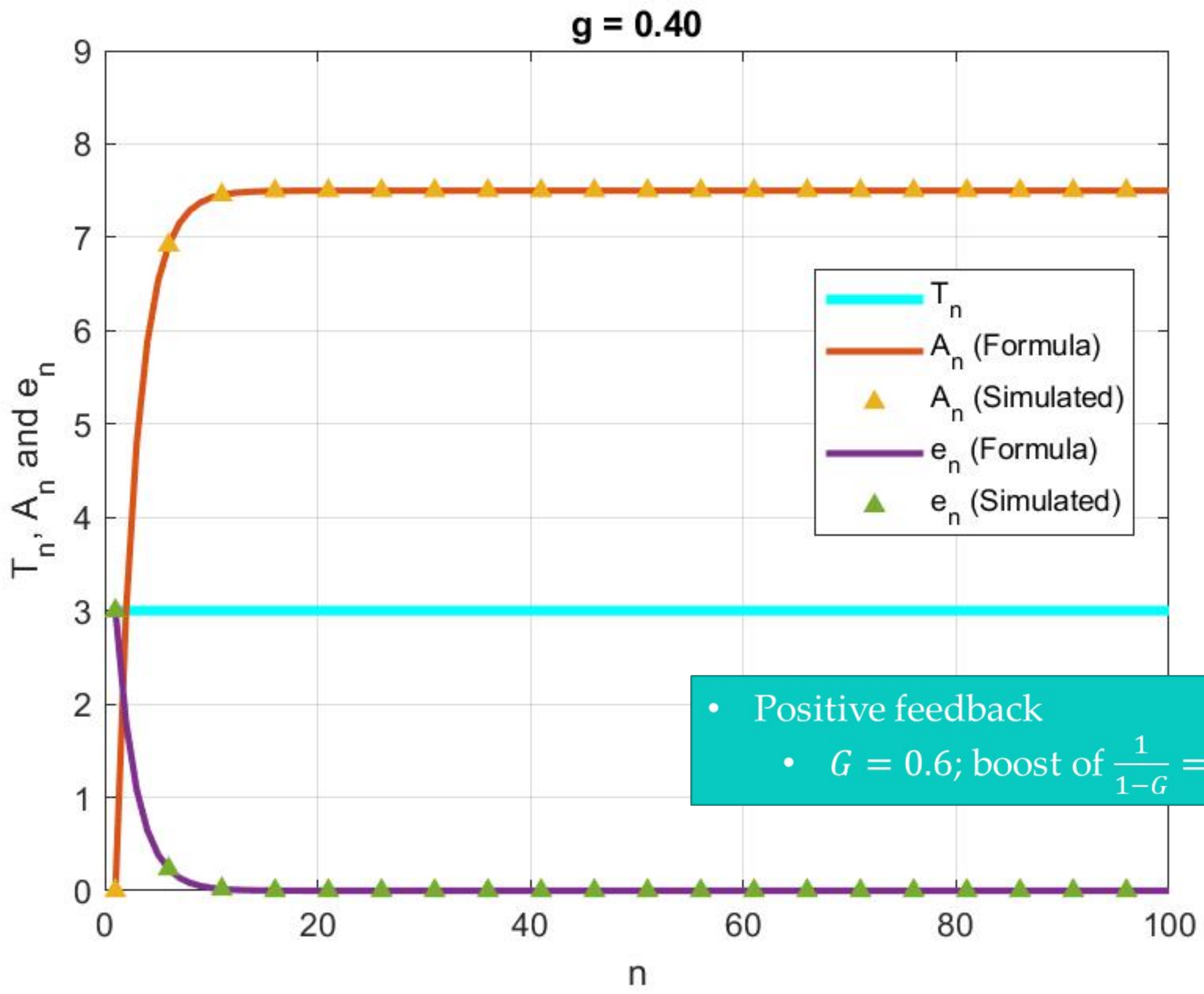
- The equations of different parameters of the feedback loop 2 on the previous slide are written below for $n = 0, 1,$ and 2
  - Here, the assumption is that the target parameter $T_n = T$ for all n, and $A_{n=0} = 0$
  - Also, we have denoted $1 - g$ as G
- **<u>Question:</u>** generalize the equations that are written for the first few values of n and derive the equations for $A_{n=N}$ and $e_{n=N}$ as a function of arbitrary loop index $n = N$ which are highlighted in the red below

0					
1					
2					

Feedback Loop 2

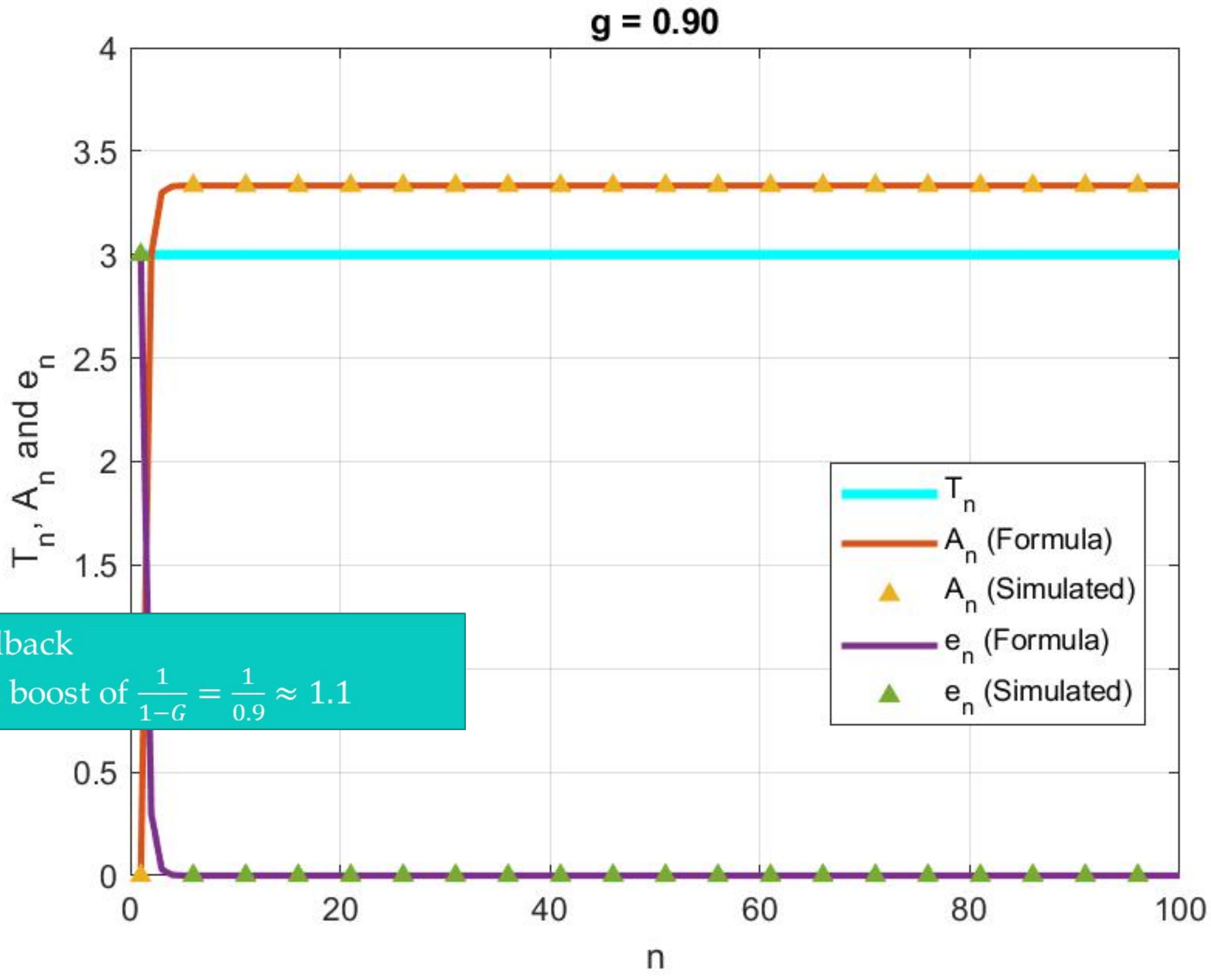


- Positive feedback
  - $G = 0.9$; boost of $\frac{1}{1-G} = \frac{1}{0.1} = 10$

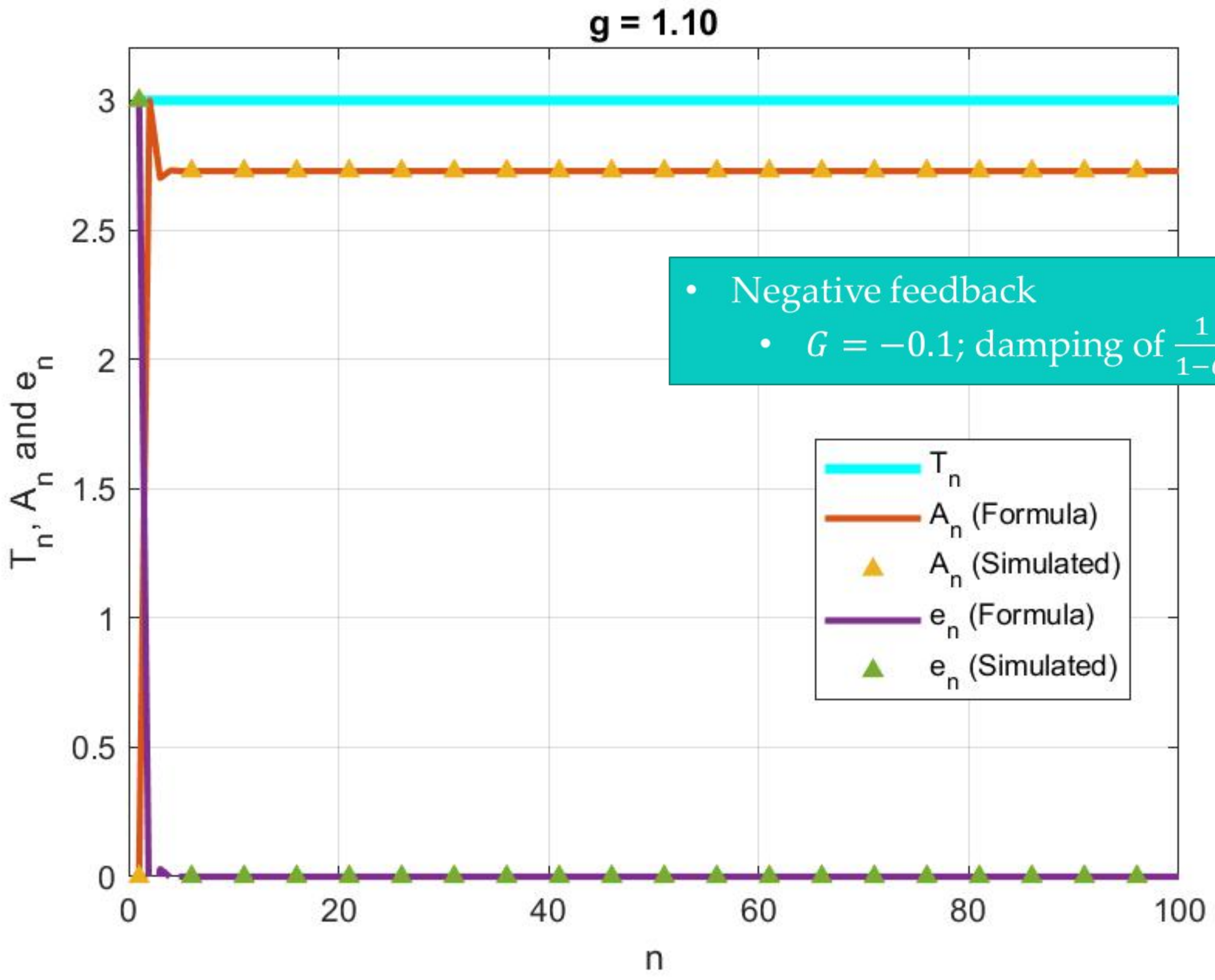


- Positive feedback
  - $G = 0.6$; boost of $\frac{1}{1-G} = \frac{1}{0.4} = 2.5$

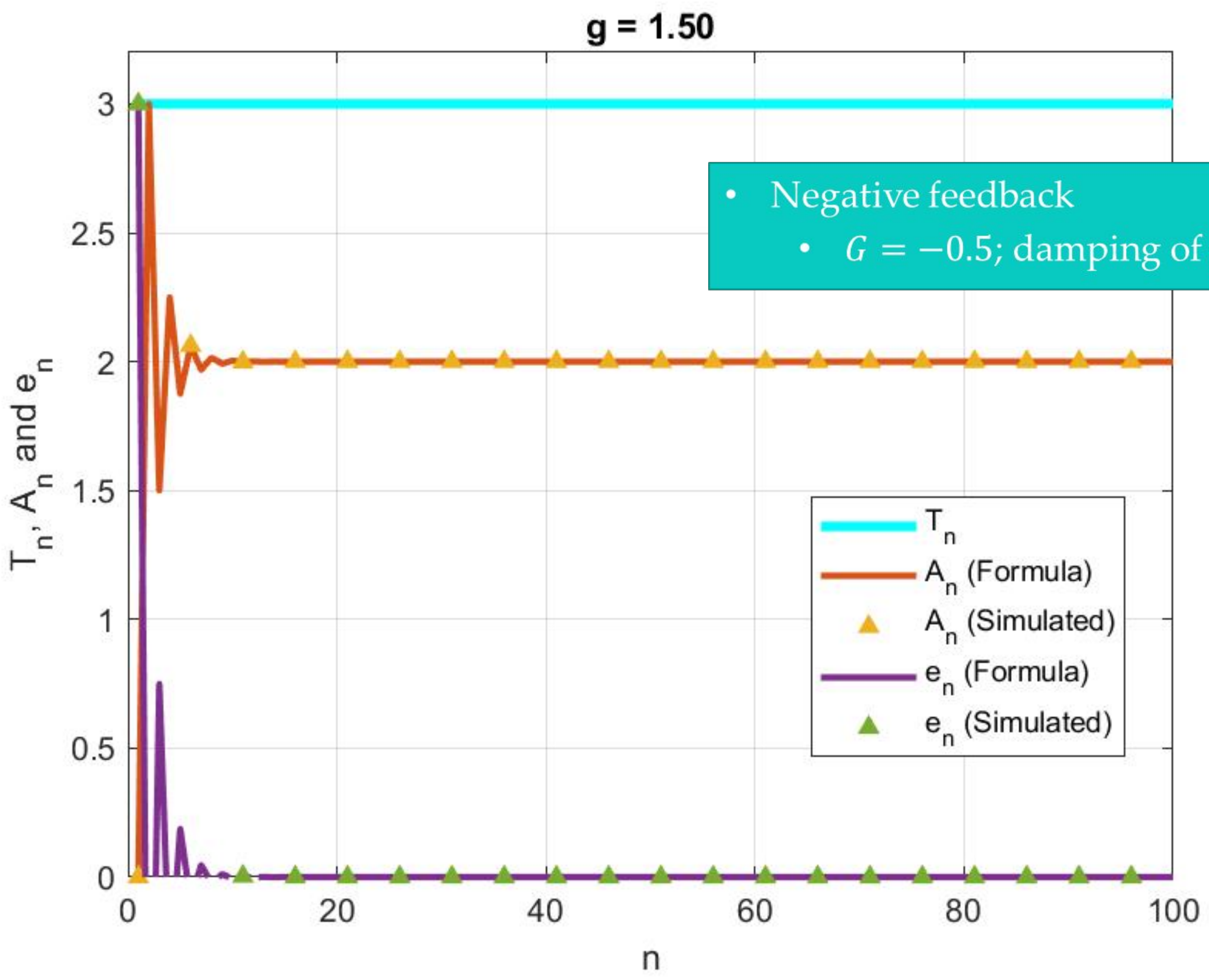
Feedback Loop 2



- Positive feedback
  - $G = 0.1$; boost of $\frac{1}{1-G} = \frac{1}{0.9} \approx 1.1$

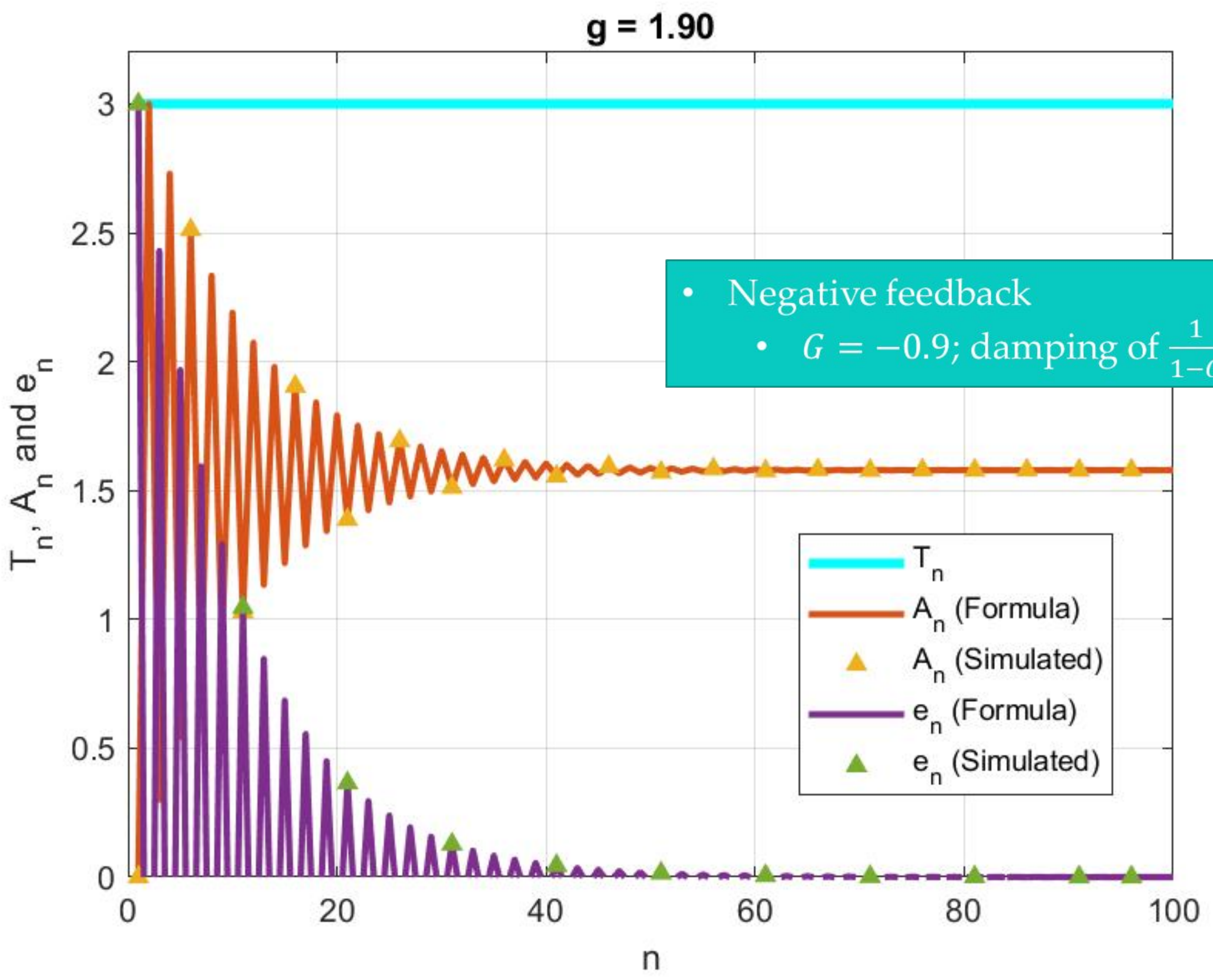


- Negative feedback
  - $G = -0.1$; damping of $\frac{1}{1-G} = \frac{1}{1.1} = 0.9$



- Negative feedback
  - $G = -0.5$; damping of $\frac{1}{1-G} = \frac{1}{1.5} = 0.66$

Feedback Loop 2



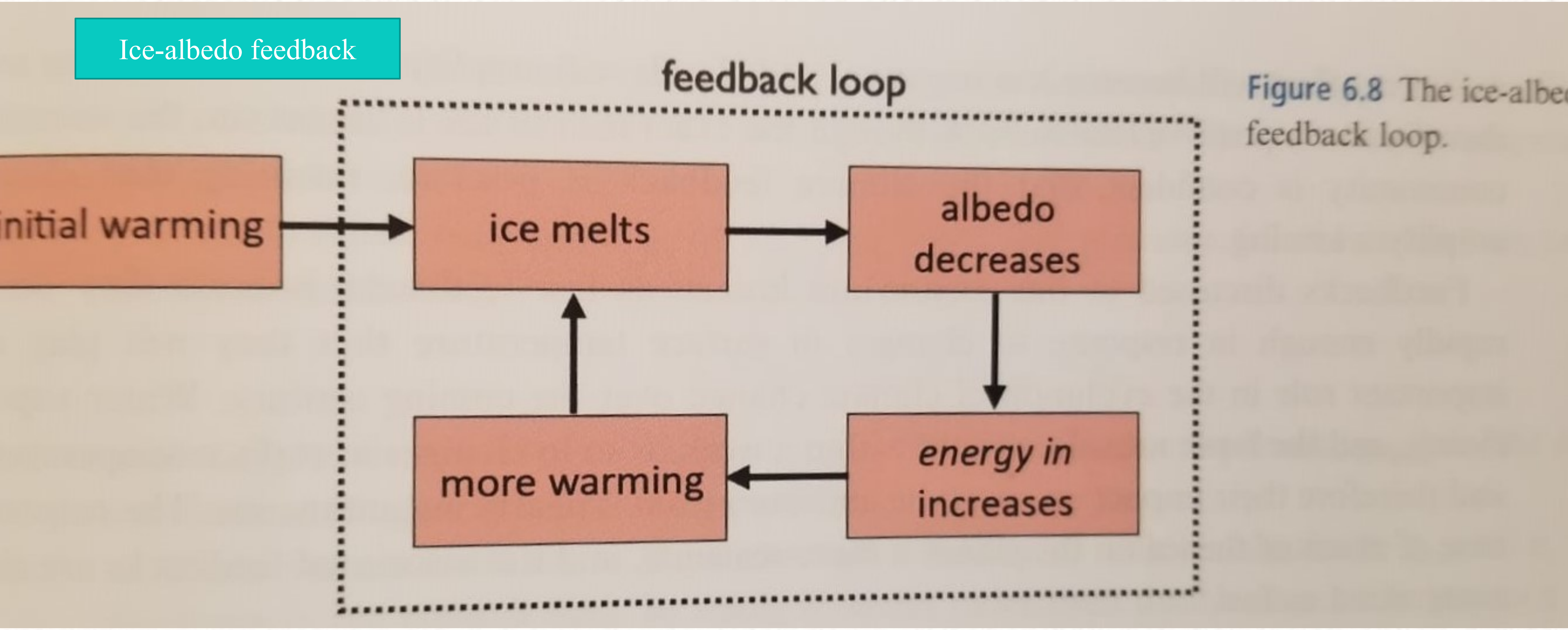
- Negative feedback
  - $G = -0.9$; damping of $\frac{1}{1-G} = \frac{1}{1.9} \approx 0.5$

Examples of Negative Feedback in Climate System

- A hypothetical planet:
  - Imagine a planet covered with flowers of two colors: white and black
  - Suppose: as the temperature of the planet goes up, the white flowers prosper and the black flowers die
  - When such a planet warms, the planet also becomes whiter, i.e., the albedo goes up, thereby cooling the planet
  - Eventually, the temperature stabilizes and the runaway effect does not occur
- Radiative Heating:
  - Power radiated equals σT^4, therefore, as the temperature increases, the power radiated increases
  - Eventually E_{out} equals E_{in} and the equilibrium is established
  - This is known as lapse-rate feedback

Examples of Positive Feedback in Climate System

Ice-albedo feedback



Water vapor feedback

A Mathematical Model of Feedback Loop 2

- Notations:
  - ΔT_i: Initial change in the temperature due to radiative forcing
  - G: amplification of this temperature due to one cycle of feedback
  - ΔT_f: final change in the temperature due to radiative forcing *and* (fast) feedback

$$\Delta T_f = \Delta T_i + G\Delta T_i + G^2\Delta T_i + G^3\Delta T_i + \cdots G^{N-1}\Delta T_i$$

$$= \sum_{k=0}^{N-1} G^k \,\Delta T_i$$

$$= \frac{1 - G^N}{1 - G} \times \Delta T_i$$

$$= \frac{\Delta T_i}{g} \qquad \text{as } N \to \infty \text{ (recall } 1 - G = g\text{)}$$

Estimated G for Earth's Climate

- The value of G for the Earth's climate is determined by four main types of feedback loops

Source of Feedback	Notation	Type	Estimated Range
Water vapor		Positive	
Ice Albedo		Positive	
Lapse Rate		Negative	
Cloud		Positive	
Total		Negative	

$$\Delta T_f = \frac{\Delta T_i}{1-G} = \frac{\Delta T_i}{1-[0.5, 0.75]} = [2,4]\Delta T_i$$

- Thus, half to $\frac{3}{4}th$ of the warming we experience comes from the feedback rather than the direct heating from the greenhouse gases

Earth's Climate Sensitivity to Doubling of CO_2

- We saw ΔT_i to be $1.2^o K$ for each doubling of $C0_2$.
- However, due the feedback effects, the final temperature increase ΔT_f is expected to be in the range of $[2.4^o K, 4.8^o K]$, with the best estimate of $3^o K$
- The climate sensitivity can also be expressed as temperature change per unit of RF
  - $[0.6^o K, 1^o K]$ per W/m^2 increase in RF, with the best estimate of $0.75^o K$ per W/m^2
  - The above can be used to answer the following question: how much warming would be produced by 5% increase in the solar constant?

Models of Future Climate Change

From a book by: Andrew E. Dessler, Introduction to Modern Climate Change, Third Edition, Cambridge University Press, 2022

A Key Equation

- The following equation relates the amount of greenhouse gas (e.g., CO_2, etc.) emissions to the three key factors that control it:

$$I = P \times A \times T$$

- Here,
  - I refers to the amount of greenhouse gas emission in CO_2
  - P: population, in number of persons in the world
  - A: Affluence, measured in $ GDP per person
  - $T = \mathrm{EI} \times CI$ is the greenhouse gas intensity
    - EI: Energy Intensity in Joules per $
    - CI: Carbon Intensity in $CO_2/Joules$

Technologies to Reduce the CI – the Carbon Intensity

- Solar Energy
  - Can supply power at 10 to 20 W/m^2 , i.e., 10 to 20 MW/km^2
  - The humankind today consumes 15×10^6 MW of power
  - This implies that the total solar panel area to satisfy the human civilization requirement would be 1 million km^2, i.e., a square of side 1000 km
- Wind Energy
  - The largest wind turbines today have rotors 160 m in length and generate 10 MW of power
  - Need a few hundreds of these to generate the same energy as a conventional fossil-fuel based power plant
  - To satisfy the humankind's needs, the wind farms containing a few million such wind turbines would be needed
- Biomass energy
  - Ethanol – a corn-based fuel – is already used in the Western countries
  - The corn uses photosynthesis to grow, which takes CO_2 out from the atmosphere, which would be released back to the atmosphere when this biofuel is burnt, thereby causing no net surplus of the greenhouse gases
  - Problems: agricultural land area requirement would become massive if adopted on a large scale. Also, this can cause the food shortages. Finally, the supplementary processes may make this a non-net-zero emission technique

Technologies to Reduce the CI – the Carbon Intensity

- Hydroelectric energy
  - Generated when the water running through a dam spins turbines and generates electricity
  - The problem is that a limit is nearly reached in terms of how much of hydroelectric energy can be generated (all the big rivers have already been dammed)
- Nuclear Energy
  - Currently accounts for roughly 16% of the World's electricity. It has several limitations:
    - Safety (nuclear reactors can malfunction or they can be overtaken by terrorists, causing catastrophic damage), how to dispose nuclear waste (some of it can be reprocessed but the remaining has to be stored, maybe deep underground), proliferation (use of nuclear waste to build bombs by rogue nations, terrorists), and the high initial cost of installing a nuclear power plant
- Carbon Capture and Storage (CCS)
  - Current technology can capture nearly 80 to 90% of the generated CO_2 by, say, a coal-fired plant
  - However, this technology still is not deployed on a mass scale and it is an expensive technology that can raise the cost of electricity

Several other technologies:

- Solar Radiation Management (increase the Earth's Albedo by injecting Sulphur compounds in the air)
- CO_2 removal from the air: direct air capture or DAC

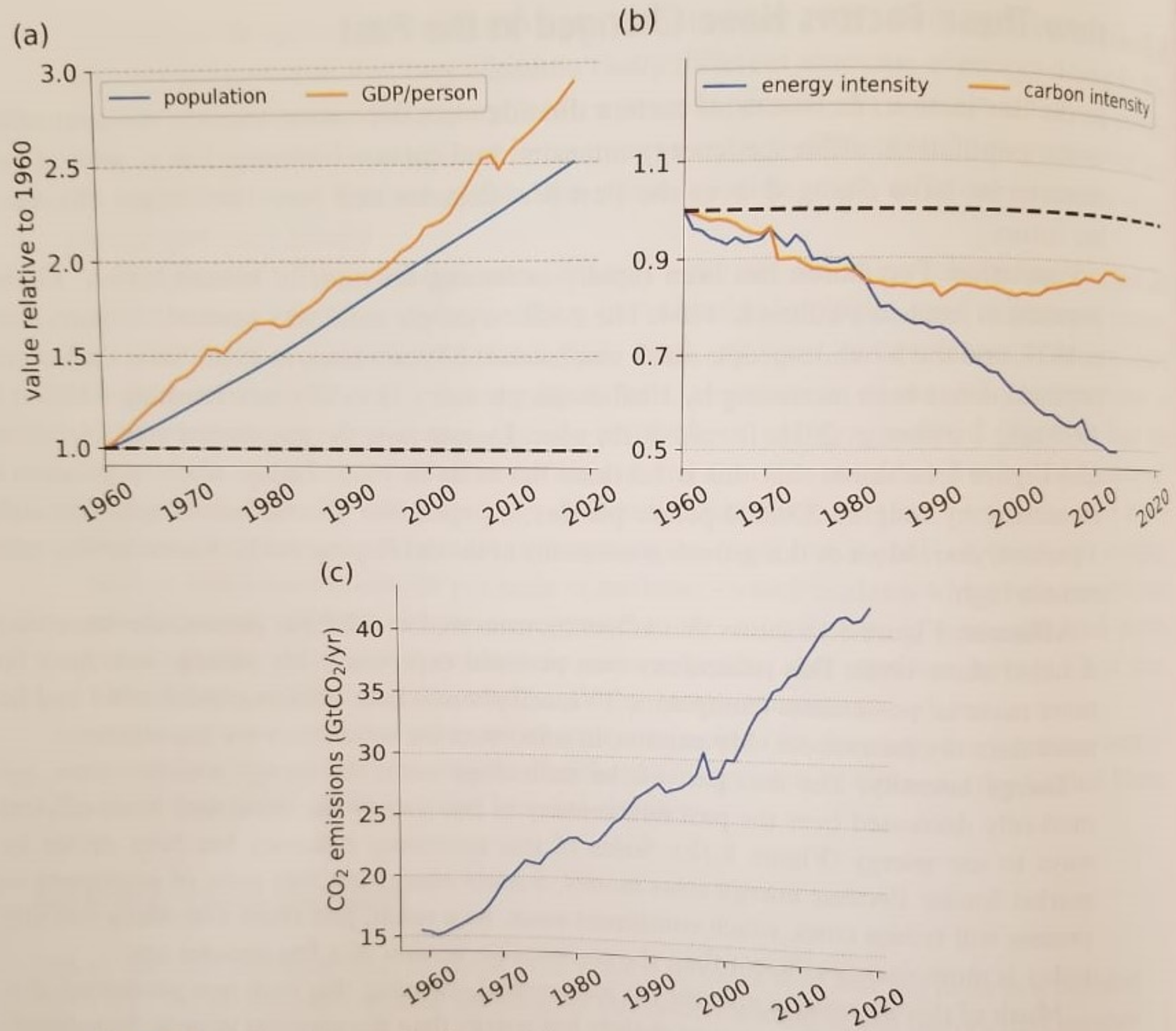


Figure 8.1 (a) Population and affluence ($/person) values, relative to values in 1960. (b) Carbon intensity (CO_2/J) and energy intensity (J/$), also relative to 1960. (c) Total emissions of carbon dioxide, in $GtCO_2$ per year. Data for population, GDP per person, and carbon intensity come from the World Bank, downloaded from https://data.worldbank.org/, retrieved June 12, 2020. Energy intensity is calculated from estimates of energy consumed and GDP downloaded from De Stercke, 2014, accessed via http://tntcat.iiasa.ac.at/PFUDB, retrieved June 13, 2020. Emissions data are described by Friedlingstein et al. (2019) and were downloaded from www.icos-cp.eu/global-carbon-budget-2019, retrieved June 9, 2020.

SSP1: Sustainability. *The world shifts gradually, but pervasively, toward a more environmentally friendly path. The world becomes a more equal place, with economic growth in poor countries causing them to close the wealth gap with the rich world. Population growth is slow, peaking in mid-century, and the world shifts towards renewable energy.*

SSP2: Middle of the road. *The world follows a path in which social, economic, and technological trends are similar to historical patterns.*

SSP: Shared Socioeconomic Pathways

SSP3: Regional rivalry. *The rich get richer, but the poor do not, leading to increasing conflict between regions. Nationalism is ascendant. Population growth is low in rich countries, but high in poorer ones. Consumption is resource-intensive and technological development is slow, leading to a reliance on high-carbon-intensity fuels like coal.*

SSP4: Inequality. *Like SSP3, the world is a divided place, but this scenario features more rapid technological development and deployment of energy technologies with low carbon intensities.*

SSP5: Fossil fueled development. *This world is similar to the optimistic SSP1 world, but it is powered by fossil fuels rather than SSP1's shift towards more sustainable energy. There is an emphasis on economic growth rather than sustainability.*

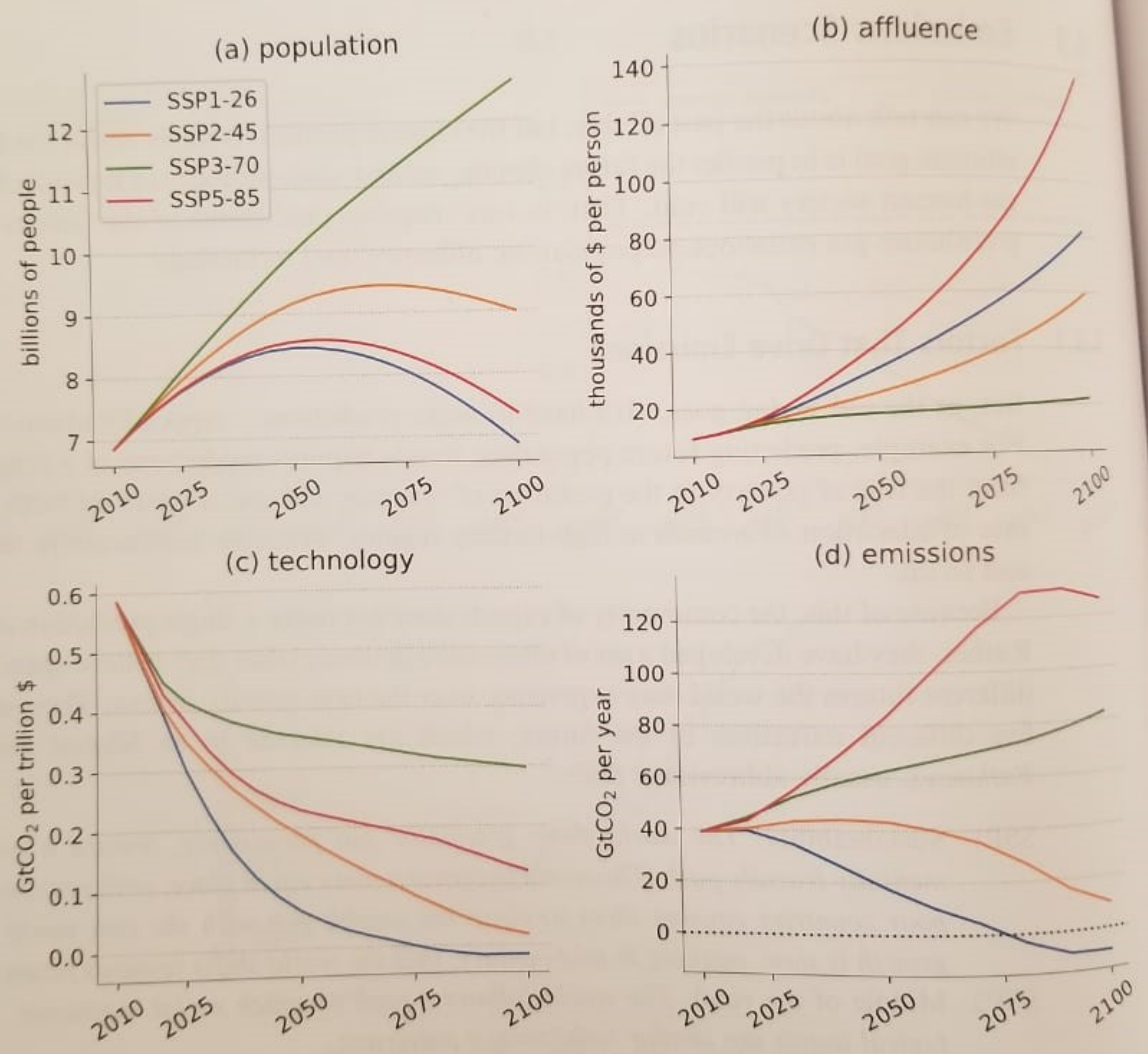


Figure 8.2 (a) Population (in billions), (b) affluence, (dollars of GDP per person), (c) technology term ($GtCO_2$ per trillion dollars of GDP), and (d) emissions of carbon dioxide ($GtCO_2$ per year). Data in panels a–c from Riahi et al. (2017), panel d from Rogelj et al. (2018) and Gidden et al. (2019), all downloaded from https://tntcat.iiasa.ac.at/SspDb, accessed July 4, 2020.

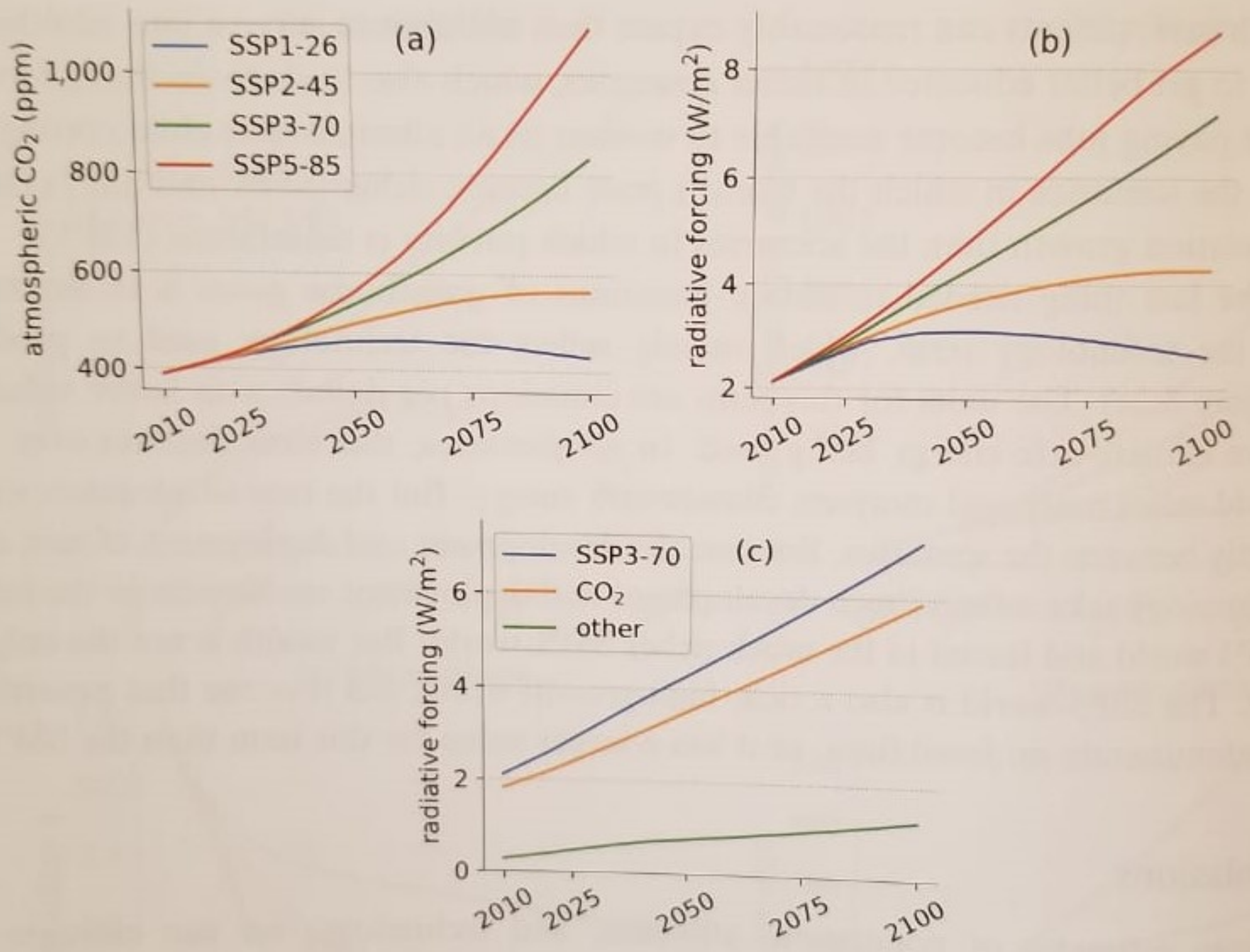


Figure 8.3 (a) Atmospheric carbon dioxide (ppm) and (b) radiative forcing (W/m^2) for four key emissions scenarios, (c) radiative forcing (W/m^2) in the SSP3–70 scenario from all constituents, from just carbon dioxide, and from everything else. This figure is based on the SSP data of Riahi et al. (2017), downloaded from the IIASA Energy Program at https://tntcat.iiasa.ac.at/SspDb, accessed July 4, 2020.

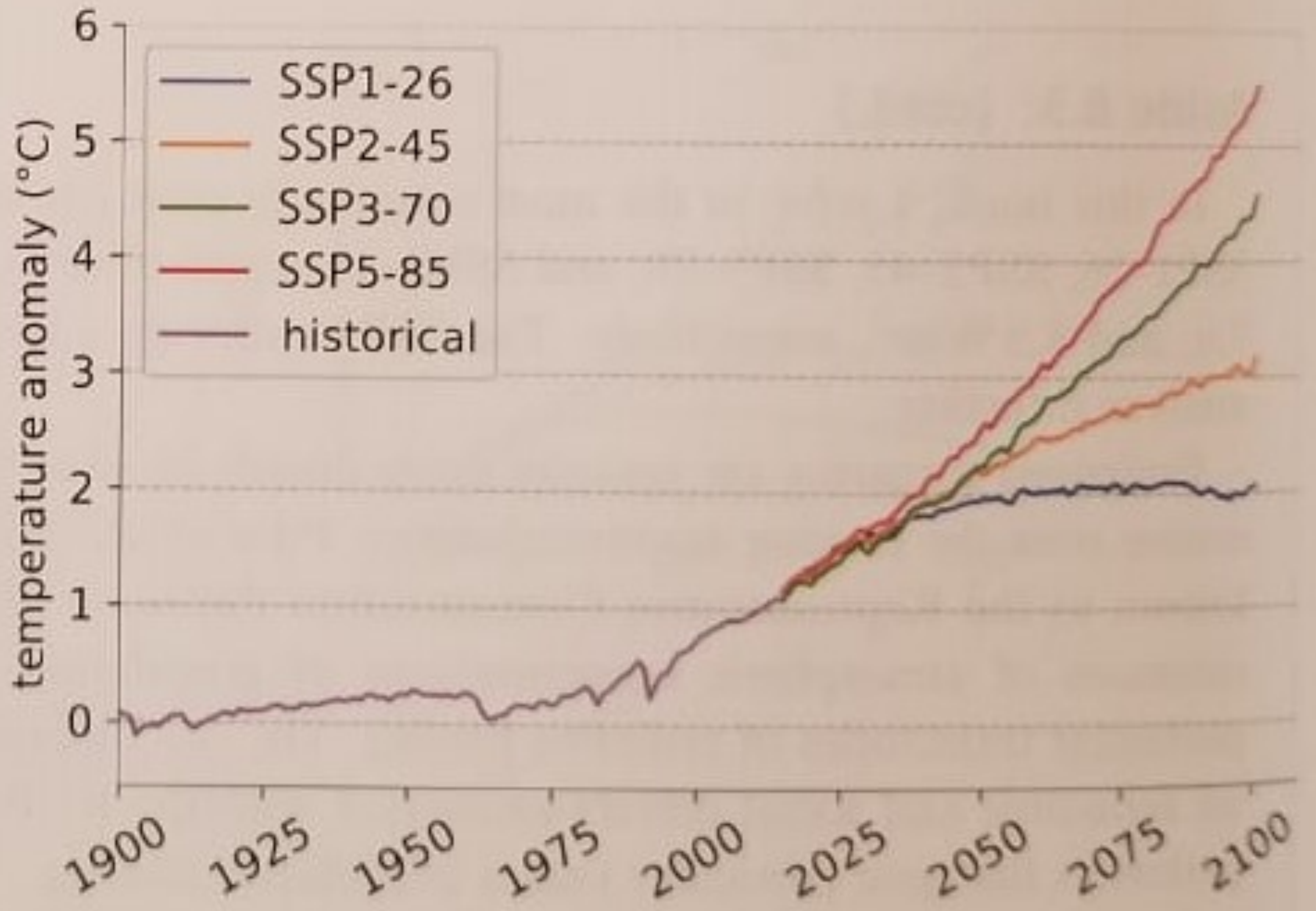


Figure 8.4 Average of 17 computer simulations of global and annual average surface temperature anomaly under four emissions scenarios. Temperatures prior to 2014 are from model runs driven by historical forcing. Estimates are from the CMIP6 model archive, processed by N. Swart, downloaded from https://github.com/swartn/cmip6-gmst-anoms, on October 16, 2020.

Why Should I Care about Climate Change?

- The models predict a warming of may be 2^o to 4^o C. This does not sound much
  - The temperature difference between the winter and the summer, or the daytime and the nighttime is many times greater than this
- The temperature on the Earth has historically been quite steady
- When the global temperature during the last ice age was 6^o C less, the Earth was basically a different planet
  - Northern latitudes were covered with the glaciers, a lot of the water was tied up in the snow/ice and the sea levels were 100 m lower compared to now
- A warming of a few degrees will remake the planet we live on
  - Many ecosystems may collapse, the agriculture may be threatened, the storms may become furious, the wet areas may become wetter and the deserts may get drier and expand, ocean will become more acidic, the sea levels may rise
- The rate of change of temperature is unprecedented
  - It took 10000 years for the planet to emerge from the last ice age, at the warming of about $0.06^o C$ per 100 years. Now, the Earth is warming few degrees per century – about fifty times faster
  - A sudden change in the climate may cause very fast changes that the human civilization may not be capable to handle

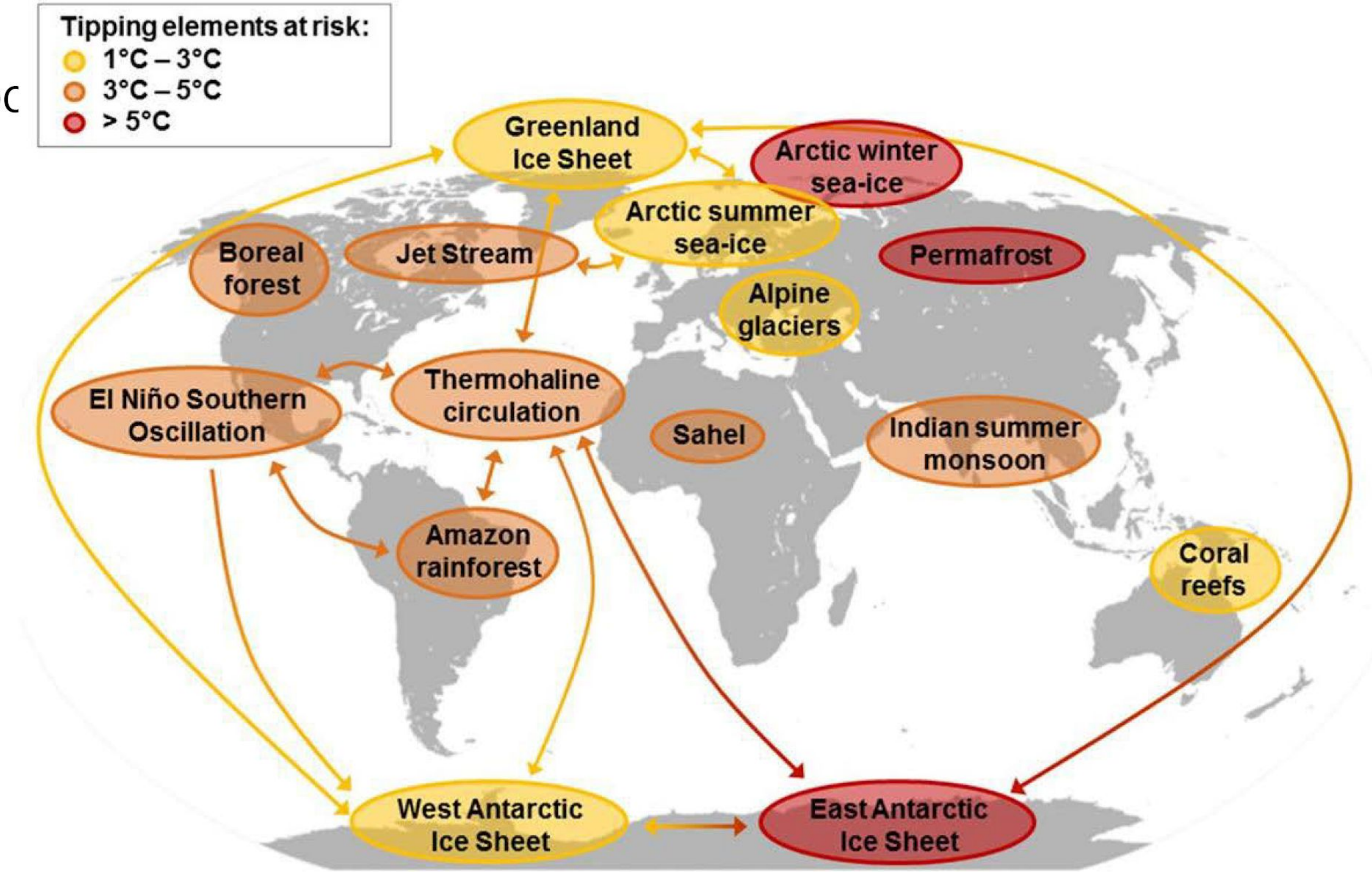
Yes, all that may be true, but the temperature has already risen up by close to $1^o C$ in the last century and I do not observe many problems

- The intensity and the frequency of the weather events have already increased
  - The summer heat is more intense than it used to be; the extreme weather events (hurricanes, the rain-storms, the forest fires, etc.) have become more frequent. However, these events are either temporally or spatially localized and we tend to forget about them once the event is over
- The climate change effects are nonlinear and exponential in nature: things are fine until suddenly one day they are not
- The effect of the climate change can precipitate the feedback loops
  - An area becomes more susceptible to the storms (forcing) (a) property rates decline (b) property tax collection reduces (c) the government services decline in the quality (d) people leave, reinforcing (a)
- The adaptation mechanisms will be needed – the proverbial wall will need to be built, either before the flood or after the flood. Either will be expensive, the latter will be more than the former
- Collapse of ecosystems may cause unwanted and unanticipated changes to our lives
  - Ecosystems provide valuable services (birds insects example, pollination by bees example)

The Concern of Hitting a Tipping Point

- Suppose you are sitting in a small boat (called a canoe) and you lean over. At the first, the canoe leans with you, but beyond a point – called tipping point – the canoe will flip over plunging you in the river
- Tipping Elements: the environmental elements at the risk due to an abrupt changes in the climate:
  - A shut-down of the Gulf steam, or Atantic Meridian Overturn Circulation (AMOC),
    - which act as a conveyer belt running in the Atlantic Ocean to transport the energy from the equator to the northern latitudes. If this ocean current stops, it could usher in big changes in the global climate
  - A rapid disintegration of the west Antarctic or Greenland ice sheets
    - Can raise the sea level by several meters in a short period of time
  - Rapid dieback of the Amazon
    - An ecological catastrophe
  - Thawing of the permafrost and methande hydrates
    - Can release a substantial amount of greenhouse gases in the atmosphere, thereby worsening the climate change
  - A shift in the timing and magnitude of the Indian monsoon
- As shown by Prof. Noerpel, the above tipping elements may be interlinked, i.e., if one element tips, it can cause the others to tip over

- Atlantic Merid. Overturn. Circulation (AMOC
- Amazon Forest Dieback (AFDB)
- Boreal Forest Dieback (BFDB)
- Arctic Permafrost Thaw (APFT)
- West African Monsoon (WAM)
- Permanent El Nino (ENSO)
- East Antarctic land-based Ice Sheet (EAIS)
- Arctic Winter Sea Ice (AWSI)
- Alpine glaciers
- Jet Stream Instability (JSI)
- Indian Summer Monsoon (ISM)
- Marine Methane Hydrates
- Marine Bio Pump Weakening
- Carbon Sink Weakening



David I. Armstrong McKay, Arie Staal, Sarah Cornell, Timothy M. Lenton, Ingo Fetzer, Climate Tipping Points: Can they trigger a Global Cascade? EGU Session: ITS3.1/NP1.2 Tipping Points in the Earth System - 6/5/20

Will Steffen, Johan Rockström, Katherine Richardson, Timothy M. Lenton,CarlFolk, Diana Liverman, Colin P. Summerhayes, Anthony D. Barnosky, Sarah E. Cornell, Michel Crucifix, Jonathan F. Donges, Ingo Fetzer, Steven J. Lade, MartenScheffer, Ricarda Winkelmann, and Hans Joachim Schellnhuber, Trajectories of the Earth System in the Anthropocene, PNAS, www.pnas.org/cgi/doi/10.1073/pnas.1810141115