Climate Change

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February 2023

Table of Contents

1 Introduction

Climate change is a vast topic, pervasive in modern-day research, and readily apparent in our own lives. It occurs periodically, due to a number of factors, particularly variations in the Earth's orbit, but is becoming increasingly anthropogenic. This handout is intended to review aspects of climate change covered in USESO administered exams. Please note that this is by no means a comprehensive guide (though it does cover advanced topics) - for your own studying, please read textbooks! Most of the information here is covered in the climate change chapter of *Meteorology Today: An Introduction to Weather, Climate and the Environment* by C. Donald Ahrens.

2 Paleoclimatology: an Overview

2.1 Oxygen-Isotope Ratios

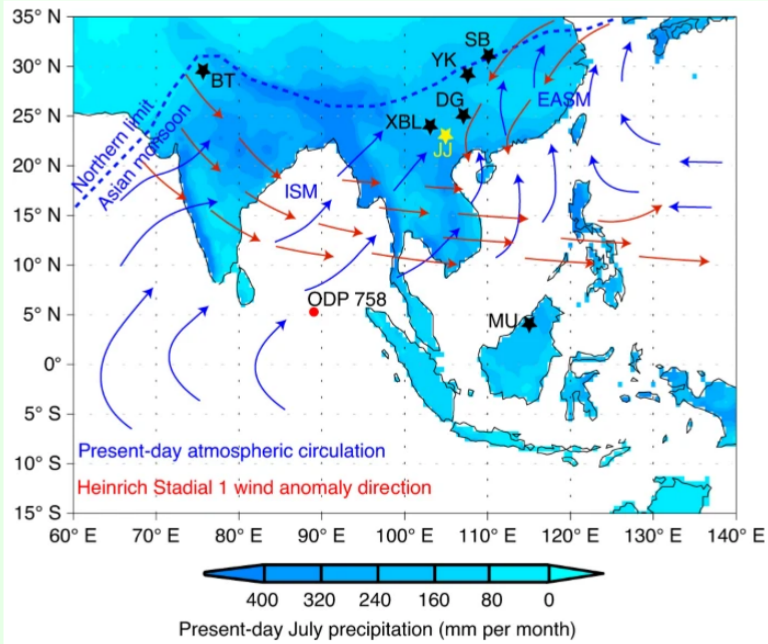
Paleoclimatologists attempt to reconstruct past climates using geologic evidence, such as landscapes, fossils, and cores taken from oceanic sediments and glacial ice. Several methods of analysis exist. A notable one is finding the **oxygen-isotope ratio** of fossils, such as calcium carbonate shells on the seafloor.

Most oxygen in seawater is oxygen-16, however, about 1/1000 of oxygen atoms have two extra neutrons (oxygen-18). Due to its higher mass, oxygen-18 tends to be left behind when seawater evaporates. Thus, precipitation on land has a higher proportion of oxygen-16. As such, oceans contain a higher concentration of oxygen-18 during periods of glacial advance, when more oxygen-16 is locked up in ice sheets rather than returned to the ocean via runoff. Thus, a higher $\frac{^{18}O}{^{16}O}$ ratio in calcium carbonate shells suggests a colder climate, while a lower ratio suggests a warmer one.

Ice cores can also be analyzed for their oxygen-isotope ratios. Generally, the colder the air when the snow fell, the richer the concentration of oxygen-16 in the core. Furthermore, air bubbles in these cores can be used to reconstruct past atmospheres. Layers of certain materials in the ice can also record causes of changes in climate. For example, the presence of sulfuric acid suggests that a volcanic eruption was responsible for a change in climate.

Example 2.1
Source: USESO Training Camp 2022 Atmosphere Exam Section I, Problem 1

The figure below shows present-day monsoon wind directions (blue) and during Heinrich events (red), where a weakened AMOC (Atlantic Meridional Overturning Circulation) shifted global wind patterns. Proxies from these events can help us understand the effects of modern climate change.



Researchers use oxygen-18 isotope concentrations as a proxy to determine the amount of precipitation at a certain time. Compared to modern records of ^{18}O, which of the following would one expect to observe in records from Heinrich events near India?

A. More ^{18}O due to more precipitation
B. More ^{18}O due to less precipitation
C. Less ^{18}O due to more precipitation
D. Less ^{18}O due to less precipitation

Solution: The Indian Summer Monsoon (ISM in figure) typically brings precipitation to India by blowing from the sea to land. The reversal of this pattern during Heinrich events would likely result in a decrease in precipitation. The lighter ^{16}O isotope is more common in precipitation than ^{18}O, so a decline in precipitation is generally associated with a decline in ^{16}O and a corresponding increase in ^{18}O. Thus, we pick choice B.

2.2 Climatic Changes during and after the Pleistocene

Throughout much of Earth's history, the global climate was much warmer than it is today. Paleoclimatologists have evidence of many periods of glaciation during the Pleistocene, and of some before. The Pleistocene epoch is characterized by an Ice Age, whose periods of glaciation have been punctuated by interglacial periods of 10,000 years or more. Observe the graph below depicting climatic trends during the Pleistocene:

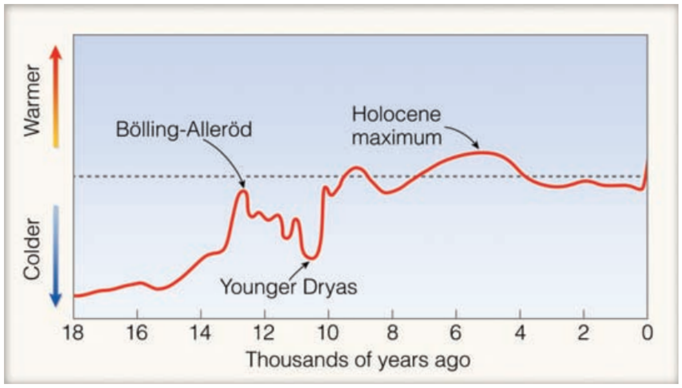


Figure 1: Climatic trends during the Pleistsocene. Note the alternating warm and cold periods experienced within comparatively short amounts of time. Causes of such climate change notably include changes in thermohaline circulation of oceans. (Source: Ahrens p.521 [13^{th} ed.])

Unlike during the Pleistocene, climatic trends in recent decades have involved a nearly constant rise in temperature. The causes of such changes are due to an increase in greenhouse gases, mainly from human activity. However, this global warming has not been uniform. The greatest warming has occurred in the Arctic and over the mid-latitude continents, particularly in winter and spring; this is because of the positive feedback loop of melting ice in the poles and the lack of circulation convection.

3 Mechanisms of Climatic Trends

3.1 Feedback Loops

3.1.1 Positive Feedback Loops

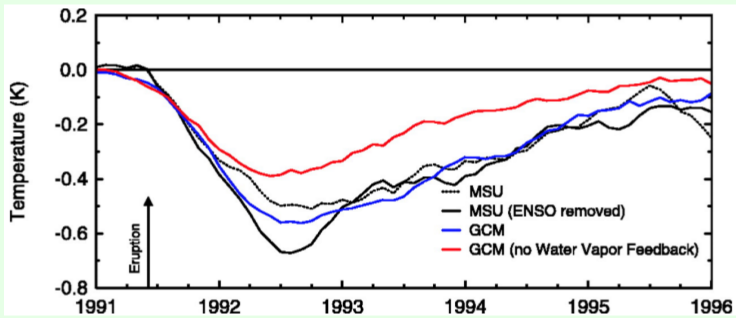
- **Water vapor-greenhouse feedback** occurs when increased temperatures increase the rate of seawater evaporation. The increased water vapor in the atmosphere increases the greenhouse effect, further accelerating warming.
- **Ice-albedo feedback** occurs when increased temperatures melt snow cover, exposing the land below. This land has a lower albedo than snow, which causes more solar energy to be absorbed, further warming the surface.

3.1.2 Negative Feedback Loops

- **Planck feedback** models the infrared radiation emitted by the Earth. It can be roughly modeled using Stefan-Boltzmann's law, $j^* = \sigma T^4$, where an exponentially positive relationship exists between j^*, representing the energy radiated by a body, and T^4, representing the body's temperature. If Earth's temperature increases, then the energy it emits to space in the form of IR radiation increases as well, causing negative feedback.
- **Chemical weathering-CO_2 feedback** is when the amount of carbon fixed increases due to accelerated chemical weathering in the presence of higher temperatures and moisture. This takes CO_2 out of the atmosphere, reducing the greenhouse effect and lowering Earth's temperature.

Example 3.1
Source: USESO 2021 Open Exam Problem 30

The figure below shows the change of the global average lower-troposphere temperature following the 1991 Pinatubo eruption. The blue and red lines represent the temperature response simulated by a general circulation model (GCM), with the red model having no water vapor feedback.



(Soden et al., 2002)

(a) Identify all of the following statements that are true. (*)

A. The eruption increased atmospheric shortwave reflectivity
B. The eruption caused atmospheric warming
C. The global response in temperature is mainly driven by the release of aerosols by the volcano
D. The presence of the water vapor feedback significantly speeds up the return of the climate to equilibrium
E. The effect of the water vapor feedback on temperature may only be seen on decadal timescales

(b) The water vapor feedback may be best characterized as a:

A. Positive feedback loop
B. Negative feedback loop

Solution: Volcanic eruptions release aerosols that increase atmospheric shortwave reflectivity. This is evidenced by the lower temperature following the eruption. Thus, A and C are true, while B is not. D is not true, because the GCM with water vapor feedback shows a slower return of the climate to equilibrium than that without water feedback. Furthermore, since water vapor feedback exacerbates the climatic trend, we can conclude that it is a positive feedback loop. E is not true because there is significant deviation between the GCM and the GCM without water vapor feedback, as we saw when considering choice D. Thus, for question (a) we pick choices A and C, and for question (b) we pick choice A.

3.2 Plate Tectonics

Plate tectonics can influence climate by changing the locations of landmasses. When there is more land in middle and high latitudes, glaciation is more likely to occur. Furthermore, plate tectonics can influence oceanic circulation, changing heat distribution (for example, isolation of a high-latitude area of ocean can cut off transport of heat through ocean currents, causing formation of sea ice). Also, subduction is responsible for outgassing, which can change the strength of the greenhouse effect by altering atmospheric composition.

3.3 Astronomical Causes

3.3.1 Milankovitch Cycles

The **Milankovitch theory** attempts to explain recurring periods of glaciation and interglacial periods on the time frame of ten thousand to one hundred thousand years, using variations in Earth's orbit. It relies on the following changes that affect solar insolation, for either the entirety (eccentricity) or parts (precession and obliquity) of the Earth:

- The **eccentricity** of the Earth's orbit varies from nearly circular to quite elliptical. This cycle takes about 100,000 years but can reach up to 413,000 years.
- The **precession** of Earth's axis refers to the cone that it traces out in space, like a wobbling top. It influences the timing of perihelion and aphelion. This cycle takes about 23,000 years.
- The **obliquity** of the Earth refers to Earth's axial tilt, which varies from approximately 22 to 24.5 degrees. This cycle takes about 41,000 years.

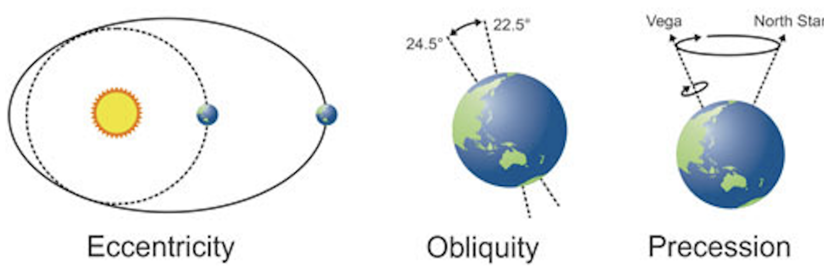


Figure 2: Factors of the Milankovitch Cycles. Eccentricity is used to describe Earth's orbit as a whole, while obliquity and precession are more detailed toward Earth's positioning. (Source: NASA Earth Observatory)

In general, the variation in insolation throughout the year is inversely proportional to the amount of glaciation. This theory cannot explain climatic variation on longer timescales, such as those before the Pleistocene.

3.3.2 Sunspot Cycles

Total solar output varies slightly (by a fraction of 1%), and cycles over 11 years, corresponding with the sunspot cycle. Total solar output is directly proportional to the number of sunspots on the sun.

3.4 Aerosols

Aerosols are microscopic liquid and solid particles that stay in the atmosphere for some amount of time, and are introduced into the atmosphere through a variety of sources, natural and anthropogenic. Most aerosols increase atmospheric shortwave reflectivity, producing an overall cooling effect on the planet. Examples include:

- **Dimethylsulfide (DMS)**, produced by phytoplankton, that can undergo reactions in the atmosphere to form reflective sulfate aerosols.

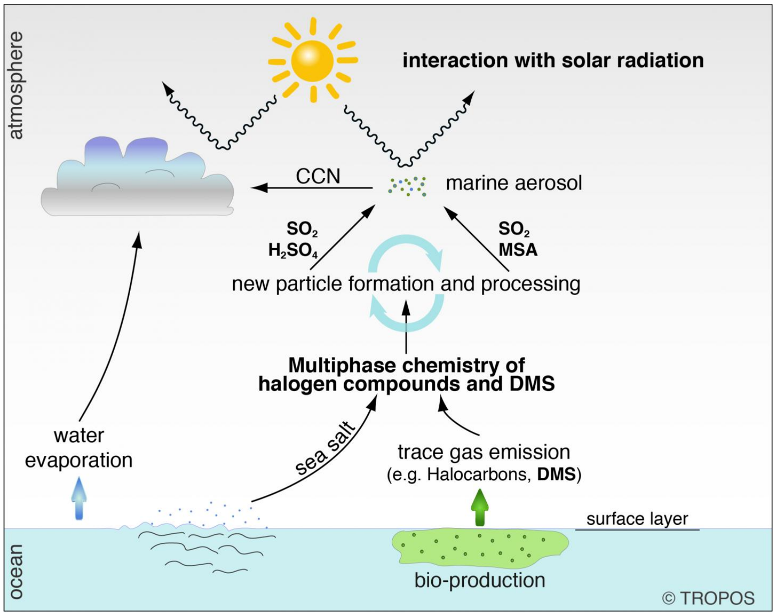


Figure 3: Reactions that produce sunlight-scattering sulfate aerosols from dimethylsulfide. This process is dependent on various biological, meteorological, and marine conditions. (Source: Hoffman et al, 2016)

- Volcanic eruptions, which are rich in sulfur gases. When ejected into the stratosphere, they form reflective sulfuric acid particles that might reside there for several years. Notable eruptions include El Chichón (1982), Mount Pinatubo (1991, see Example 3.1), Mount Tambora (1815), etc. Such eruptions have a notable cooling effect in the troposphere. However, some aerosols released also have the effect of warming the lower stratosphere by absorbing radiation emitted by the Sun and Earth. This does not happen evenly, and the tropical stratosphere becomes much warmer than the polar stratosphere, producing a strong upper-level pressure gradient and strong zonal stratospheric winds. These winds work their way down into the upper troposphere, where they direct maritime air onto continents, producing warmer winters over the Northern Hemisphere during the first year or two following the eruption.

- Dust storms, which sweep many small particles, such as clay, into the atmosphere.

- Wildfires, which produce aerosols like soot, which mingle in the atmosphere. These soot particles are classified as **black carbon (BC)** aerosols, which, unlike most other aerosols, tend to absorb shortwave radiation, producing a warming effect. Thus, wildfires can be loosely thought to belong to a positive feedback loop. Black carbon is also released by anthropogenic combustion processes. Note that other aerosols compensate for black carbon radiation absorption because of their high reflectivity, so that the net effect of aerosols is to cool the Earth.

- Sulfur pollution, that forms highly reflective sulfur aerosols. They are primarily produced by combustion of fossil fuels, such as coal, and jet fuel (contrails). Sulfur pollution enters the atmosphere mainly as sulfur dioxide gas. There, it transforms into tiny sulfate droplets or particles. Because these aerosols usually remain in the lower atmosphere for only a few days, they do not have time to spread around the globe. Hence, they are not well mixed and their effect is felt mostly over the Northern Hemisphere, especially over polluted regions. Sulfate aerosols can also serve as cloud condensation nuclei, forming clouds that reflect even more incoming shortwave radiation back to space.

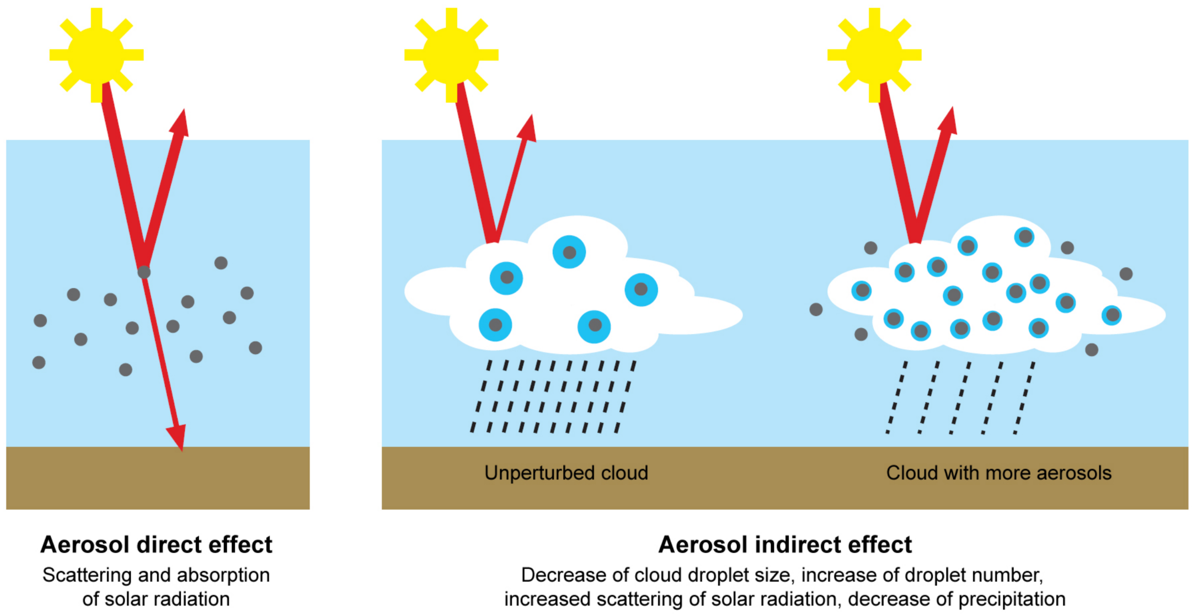


Figure 4: Along with increasing cloud cover by acting as condensation nuclei, the chemical composition of aerosols determines the extent of light energy absorption or reflection. (Source: Federal Office of Meteorology and Climatology MeteoSwiss)

3.5 Greenhouse Gases

Greenhouse gases contribute to global warming by reflecting outgoing longwave (IR) radiation back to the surface of the Earth, trapping heat. When the rate of the incoming solar energy balances the rate of outgoing infrared energy from Earth's surface and atmosphere (mediated by the greenhouse effect), the Earth-atmosphere system is in a state of **radiative equilibrium**. Increasing concentrations of greenhouse gases can disturb this equilibrium and are thus referred to as *radiative forcing agents*.

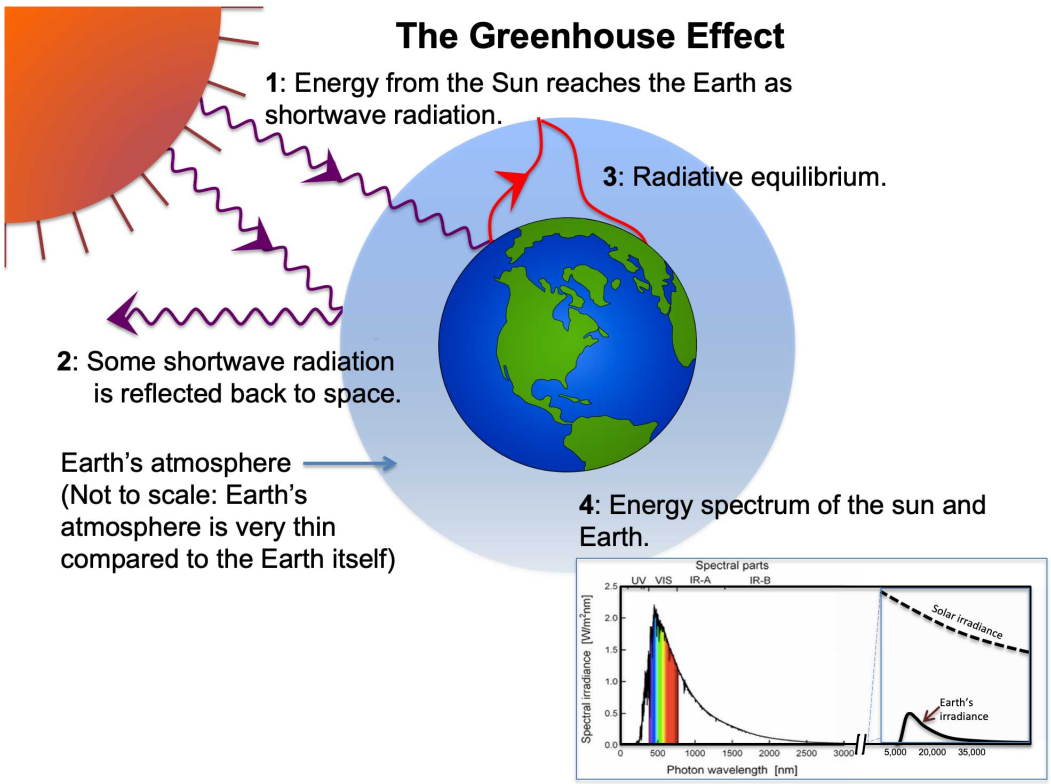


Figure 5: An increase in the strength of the greenhouse effect reflects a trend towards net radiative heating through positive radiative forcing. (Source: Paleontological Research Institution)

Radiative forcing is defined as a change in the radiant energy (W/m^2) observed over an area in the middle of the tropopause. The radiative forcing provided by extra greenhouse gases has increased by about 3 W/m^2 in the past few hundred years. The table below depicts the impact each major greenhouse has on net radiative forcing:

	Concentrations[b] and their changes[c]		Radiative Forcing[d]	
Species[a]	2005	Change since 1998	2005 ($W\ m^{-2}$)	Change since 1998 (%)
CO_2	**379 ± 0.65 ppm**	**+13 ppm**	**1.66**	**+13**
CH_4	**1,774 ± 1.8 ppb**	**+11 ppb**	**0.48**	**-**
N_2O	**319 ± 0.12 ppb**	**+5 ppb**	**0.16**	**+11**
	ppt	ppt		
CFC-11	251 ± 0.36	–13	0.063	–5
CFC-12	538 ± 0.18	+4	0.17	+1
CFC-113	79 ± 0.064	–4	0.024	–5
HCFC-22	169 ± 1.0	+38	0.033	+29
HCFC-141b	18 ± 0.068	+9	0.0025	+93
HCFC-142b	15 ± 0.13	+6	0.0031	+57
CH_3CCl_3	19 ± 0.47	–47	0.0011	–72
CCl_4	93 ± 0.17	–7	0.012	–7
HFC-125	3.7 ± 0.10[e]	+2.6[f]	0.0009	+234
HFC-134a	35 ± 0.73	+27	0.0055	+349
HFC-152a	3.9 ± 0.11[e]	+2.4[f]	0.0004	+151
HFC-23	18 ± 0.12[g,h]	+4	0.0033	+29
SF_6	5.6 ± 0.038[i]	+1.5	0.0029	+36
CF_4 (PFC-14)	74 ± 1.6[j]	-	0.0034	-
C_2F_6 (PFC-116)	2.9 ± 0.025[g,h]	+0.5	0.0008	+22
CFCs Total[k]			**0.268**	**–1**
HCFCs Total			**0.039**	**+33**
Montreal Gases			**0.320**	**–1**
Other Kyoto Gases (HFCs + PFCs + SF_6)			**0.017**	**+69**
Halocarbons			**0.337**	**+1**
Total LLGHGs			**2.63**	**+9**

Figure 6: Radiative forcing contributed by major greenhouse gases (Source: IPCC, 2018)

A significant portion (approximately 0.8 W/m^2) of this radiative forcing is offset by other factors, such as aerosols and solar activity. This, combined with the fact that according to the Milankovitch theory, Earth would currently be in a cooling trend, lessens the degree to which our planet is warming.

4 Conclusion

I would like to conclude by noting that Earth's climate is dependent on a variety of different factors, all of which are interconnected:

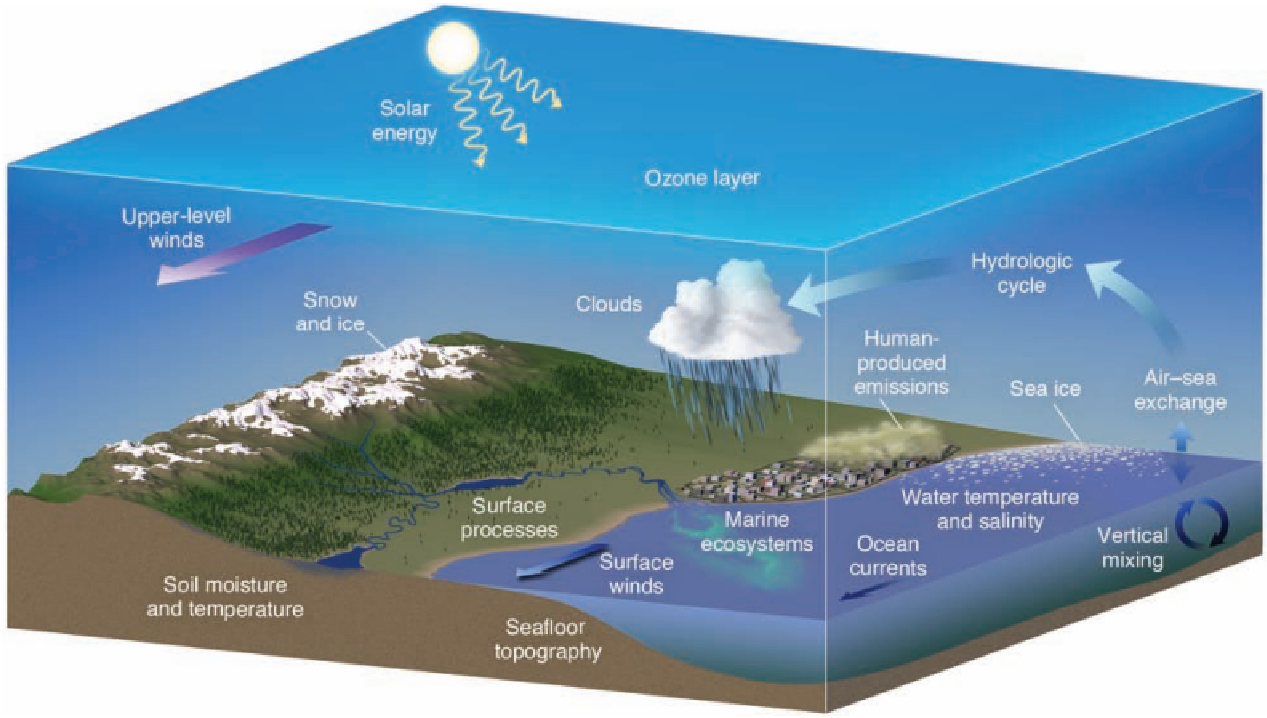


Figure 7: general circulation model (GCM) of the Earth system. (Source: Ahrens p.541 [13th ed.])

If you are confronted with questions about climate change on the exam, take a moment to think about how the mechanism in question might be interconnected with the rest of the Earth system, as it can provide further insight to help you solve the problem.

If you have further questions, read Ahrens, or research online. Good luck!