THE GREENHOUSE EFFECT AND GLOBAL WARMING

CHAPTER 6

Note to Reviewers: This chapter, as it stands, is too long. My intention is to tuck a significant number of sections in the chapter away in links for the students who wish to dig more deeply into particular subjects. Please indicate which sections you think should be treated in this manner.

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A **greenhouse** is a location for the production of flowers and other plants. The Sun's heat is trapped by greenhouse gas molecular window panes. The **greenhouse effect** is

a well-established fact based on well established scientific theory. It explains how certain gases, designated "**greenhouse gases**," trap radiant energy from the Sun-warmed Earth, causing increased heating of an atmosphere containing those gases. **Global warming** is both a scientific fact – the Earth has warmed in the past century – and a prediction of what is likely to happen in the future caused by continually increasing concentrations of atmospheric greenhouse gases. There is no dispute that the concentrations of certain critical greenhouse gases, such as carbon dioxide, have been increasing in the last century. **Climate change** is the collective term udes to describe complex changes in weather patterns in the past and in the present, and those predicted to accompany increasing concentrations of greenhouse gases.

What are the known facts? What is the science? What are the theories? We will first examine the underlying chemical principles involved in this debate, in particular, the scientific basis for the greenhouse effect. Then we will review the existing conditions and study the predictions made by scientists regarding the problem.

Questions Addressed in This Chapter

1. What is the mechanism of the greenhouse effect?
2. What are the characteristics of photons?
3. What do photons and molecules have in common?
4. Why might an infrared photon interact with a greenhouse gas molecule?
5. What is the historical connection between global temperature and greenhouse gas concentrations?
6. What are the reasons to think that rising greenhouse gas concentrations may have detrimental consequences on global climate?
7. What are the assumptions and limitations of computer models that predict future global temperatures?
8. What are the definitions of the following climate change terms: climate forcing, feedback, and impact?
9. What is the nature of the controversy regarding global climate change?

The Greenhouse Effect (An Overview)

The greenhouse effect is so named because the Earth functions in some ways like a greenhouse. In the latter structure, visible sunlight penetrates through a glass enclosure and warms the plants and their surroundings, and the resulting heat generated by the absorbed sunlight inside the greenhouse is partially prevented from escaping by the glass enclosure. In much the same manner, visible and some infrared and ultraviolet sunlight penetrate the Earth's atmosphere, are absorbed by substances on the Earth’s surface, warming them, and the resulting heat radiating from these substances is temporarily trapped by molecules in the Earth's atmosphere. This molecular trapping is accomplished by greenhouse gases, including water vapor.

The Greenhouse Effect

Greenhouse gases represent a very small fraction of atmospheric gases. However, without greenhouse gases, the temperature of the Earth would be too low to sustain life as we know it. Without the greenhouse effect, the average global temperature of the Earth would be some 33° C (60° F) lower. This is because these gases absorb significant amounts of heat radiated from the sun-warmed Earth that would otherwise escape immediately into outer space. Instead, heat is temporarily trapped by greenhouse gases, raising the temperature of the trapping gas and surrounding atmosphere.

A **greenhouse gas** is more scientifically defined as a gas in the Earth’s troposphere that absorbs infrared radiation emitted by the sun-warmed Earth, and re-emits this absorbed energy again as infrared radiation, thereby warming the Earth's surface and troposphere. This definition gives rise to many questions: What is infrared radiation? Why is it given off by the sun-warmed Earth? Why and how does infrared radiation interact with greenhouse gases? What are the consequences of this interaction? How does this interaction lead to higher atmospheric temperatures? To answer these questions, we first investigate the fates of sunlight photons entering the Earth’s atmosphere. We must also explore the motions of atoms within individual gaseous molecules, the nature of electromagnetic radiation, and relate these to the temperature of the atmosphere.

The Mechanism of the Greenhouse Effect

Incoming sunlight can experience one of four atmospheric fates (Fig. 6-1):

(1) reflection or scattering by clouds;
(2) reflection by the substances on the Earth’s surface;
(3) absorption by substances on the Earth’s surface;
(4) absorption by clouds, water vapor or dust.

The fraction of the total incident sunlight reflected back into space is known as the Earth’s **albedo.** For example, the average albedo of the Earth is 0.3, which means that 30% of the incident solar energy is reflected or scattered back into space. Approximately 46% of the sunlight entering the Earth’s atmosphere is absorbed on the Earth surface. A small fraction of this incoming solar energy is used to convert

CO_2 and H_2O into plant material. Objects are warmed by conversion of absorbed sunlight energy into energy of the object's molecular or atomic vibrations. A significant part of the absorbed sunlight energy that heats materials on the Earth is eventually emitted (given off) back into the atmosphere in the form of shortwave **infrared (IR)** (Figs. 6-1 and 6-2).

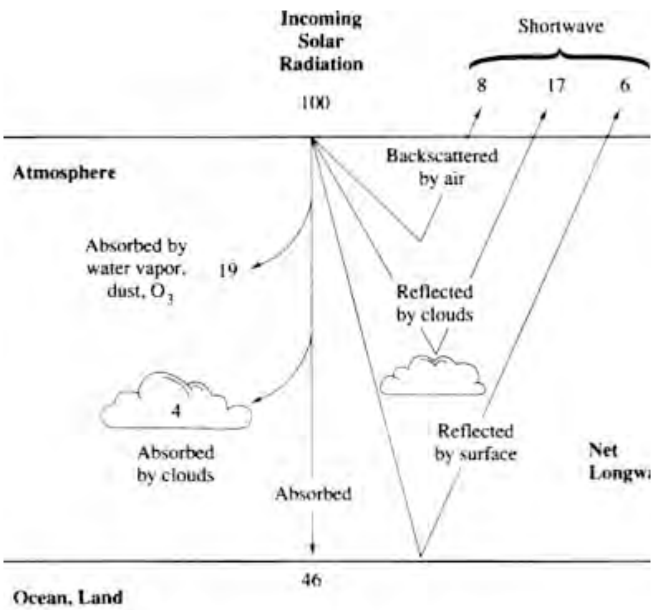

Fig. 6-1 Fates of shortwave (mainly UV, visible) sunlight entering the atmosphere. Numerals are percentages of the incoming solar energy involved in the different processes.

Mechanism of the effect

The Earth is an **open system**. That is, energy from the Sun is continually pouring into the Earth's atmosphere on its side facing the Sun. For preservation of life as we know it, we prefer that the *average* global temperature be constant and not be continually rising because of a large solar energy input. The only way this can happen is if there is an amount of energy emitted back out into space from the Earth that is *on average* equal to the amount of energy entering the atmosphere from the Sun. Of 100 units of incoming solar energy, mostly in the visible wavelengths, about 30% is reflected back to space (this is "Earth-shine"). The rest is absorbed in the atmsophre (about 25%) or heats the Earth's surface. Infrared radiation emiited from Earth is responsible for 70 of these 100 units of energy that excape back into space. (Fig. 6-2).

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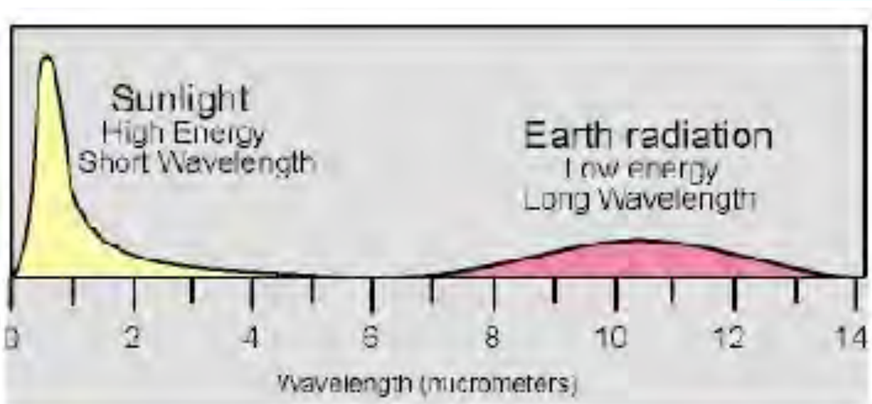

Fig. 6-2. Differences in wavelengths of radiations emitted by the sun and the infraared photons given off by the sun-warmed Earth

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What happens to the 46% of the sunlight that is absorbed on the Earth's surface? Certainly one of the most important uses is to drive both natural and agricultural photosynthetic processes. The rest of the energy is present in the absorbing objects as heat, heat that drives three different processes. One, called **sensible heat**, is heating of the atmosphere around the object. The second uses this heat to evaporate water providing **latent heat** that is available to the atmosphere upon condensation of this water vapor to liquid. The third and rest of this absorbed heat is emitted by the Earth's surface as **long wavelength infrared (IR) radiation**. *It is this radiation that is responsible for the greenhouse effect and that is primarily responsible for global warming*. These three types of heat energy transfer to the atmopshere are the primary driving factors in the Earth's weather system.

Any heated substance spontaneously loses a part of its energy by emitting infrared photons. Instead of observing IR photons with your eyes, you feel the effects of absorbed IR photons when, after being absorbed by your skin, the absorbed energy causes the atoms that make up the molecules of your skin to vibrate more rapidly. This more rapid vibration is sensed by the brain as heat. The heat you feel at a distance from a hot stove or fireplace is streaming infrared photons that are absorbed by your clothing or skin.

Vibrating molecules and atoms in sun-warmed objects such as soil or a hot pavement slow down their vibration slightly after they give off infrared photons and the radiating object cools. As these infrared photons from the sun-warmed Earth pass through the atmosphere, they can undergo one of three different fates. They are absorbed by either clouds or greenhouse gases, or, much less likely, they can escape into space at the speed of light. When the infrared radiation is absorbed by greenhouse gas molecules (including water vapor), they increase their molecular energy. When they undergo molecular collisions, they cause surrounding molecules to increase their energy. Thus the temperature of

Fate of infrared (IR) radiation from sun warmed earth

Each of these molecules can re-emit infrared radiation. Part of this re-radiation can be absorbed on Earth, reheating it. Thus the cloud cover and the infrared-absorbing greenhouse gases act like greenhouse window panes to delay, but not prevent, the escape of heat created by visible sunlight streaming through those same windows. The greenhouse effect mechanism isn't exactly the same as that in a florist's greenhouse, but the heat-trapping processes in some ways are similar. In the greenhouse effect, IR photons are *continually* being exchanged between the earth, the clouds, and greenhouse gases. Heat does escape through real greenhouse windows, and IR photons do ultimately escape the Earth into outer space, most of them from the upper atmosphere. Otherwise the Earth would continue to heat up and life would be exterminated as it would be on the planet Venus. But this continual IR photon exchange is responsible for the heating of the lower atmosphere before IR photons escape to outer space from the upper atmosphere.

Greenhouse gas molecules absorb infrared photons

Most complex molecules absorb infrared radiation. Nitrogen and oxygen molecules together make up over 99% of the gases in the Earth's atmosphere. However, neither of these molecules is a greenhouse gas. The other naturally-occurring gases in the atmosphere, such as carbon dioxide (CO_2), water (H_2O), nitrous oxide (N_2O), methane (CH_4), and manufactured gases such as chlorofluorocarbons (CFCs) absorb significant numbers of IR photons, despite their small concentrations in the atmosphere. Why do some atmospheric gases absorb and some do not absorb infrared radiation? The answer involves the types of motions light photons and

IR absorbed by trace gases

greenhouse gas molecules udergo.

Characteristics of light, an electromagnetic radiation

Speed of light

Light is not easily understood because it has the characteristics of both a particle and a wave. **Photons**, which may be thought of as classical particle-like wave packets, exist in many different energy forms. The wide variety of photons has already been introduced in the **electromagnetic spectrum** illustrated in Fig. 2-2. Every electromagnetic radiation (photon) travels through a given material, in air, for example, with the same speed. Blue light, red light, FM and TV photons, gamma and X-rays all travel in air with the same speed, namely, 186,000 miles per second. Another way of looking at this speed is that all photons travel in air one foot or 30.5 centimeters in one nanosecond (10^{-9} s = 0.000000001 seconds). That's fast!

Example 6-1 **Speed of light**

How fast, in miles per hour, does a blue photon travel through air?

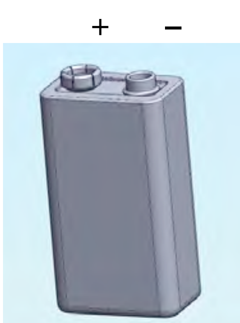
Beware of the color of the photon in this wording. Any photon, blue, red, or green light, an X-ray, or an infrared photon travels with the same speed through air.

$$?? \frac{\text{miles}}{\text{hour}} = 1.86 \times 10^5 \frac{\text{miles}}{\cancel{\text{sec}}} \times \frac{60 \cancel{\text{sec}}}{1 \cancel{\text{min}}} \times \frac{60 \cancel{\text{min}}}{1 \text{ hour}}$$

$$= (1.86 \times 10^5 \times 60 \times 60) \text{ miles/hour} = 6.70 \times 10^8 \text{ miles/hour}$$

$$= 670{,}000{,}000 \text{ miles per hour} \quad \text{(Again, that's fast!)}$$

Electric characteristics of light



Dipole: electric

To comprehend better the nature of electromagnetic radiation (photons), we break up the word electromagnetic into its component parts. "Electro-" means it has characteristics associated with electric charges (positive and negative charges), and "–magnetic" means it has characteristics that are associated with magnetic fields (north and south magnetic poles). Even though we can't easily comprehend the concept of a photon, we can understand the properties of a photon by its actions.

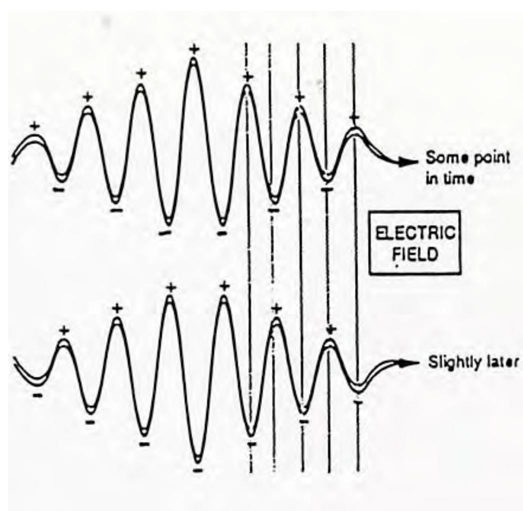


Fig. 6-3 Oscillation electric fields in a moving photon wave packet

Ch6/PhotonCharacteristics/p.3

Each photon behaves as though it were an oscillating electric and magnetic dipole (dipole means containing two poles, e.g., + and – electric charges, and N and S magnetic poles, as in a permanent magnet.) That is, a photon behaves as though it were something in which the wave packet is oscillating up and down between positive and negative values (Fig. 6-3) and between N and S at the same time. We will concern ourselves only with the electric dipoles of photons.

The electric positive and negative charges alternate over time with a certain **frequency**, or number of complete cycles of change per second(Fig. 6-4). At the end of one cycle, the wave packet is identical to what it was at the beginning of the cycle, except for its location in space, since it must move with the speed of light while oscillating. Photons are characterized by the frequency of these oscillations. The only difference between X-rays, radio waves, blue light, and infrared light lies in their frequency and a directly related quantity, the **wavelength**. The frequency of a light wave is measured by the number of peaks (crests) passing a given point during a given time span. Consider being on a pier jutting into the ocean counting waves go by. The wavelength is much like the distance between the crests of the ocean waves.

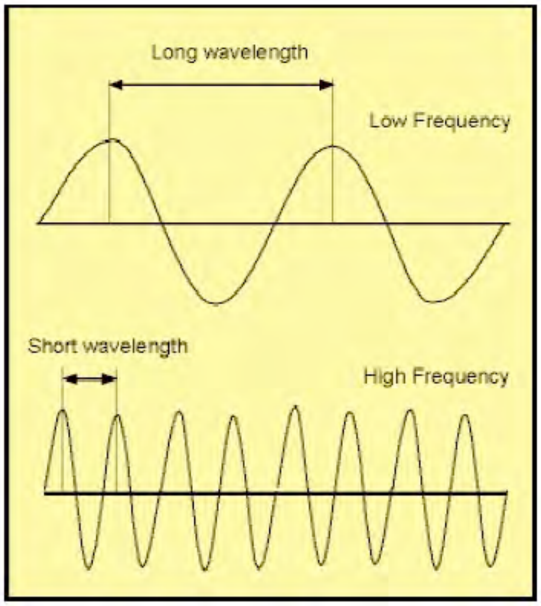


Fig. 6-4 Wavelength and frequency of Two different electromagnetic radiations. Nodes, points on the curves where they cross the horizontal line, do not move away from that line.

Ch6/PhotonCharacteristics/p.1

As shown in Fig. 6-4, decreasing the frequency increases the wavelength. That is, fewer wave crests pass a stationary observer during a given time period. An ocean wave moves with a velocity far slower than the speed of light, but has a relatively easily measured distance between wave peaks. The wavelengths of infrared photons are small fractions of a millimeter and cannot be measured with ordinary measuring devices because they are so small and because the IR photons travel with the speed of light.

If one is interested in the energy of the photon, it is probably easier to remember that the energy is directly proportional to the frequency. It might help to recognize that it takes more energy to wave your hand up and down fast in a cyclic motion than more slowly. Increasing the frequency of a photon increases its energy. Decreasing its frequency decreases a photon's energy.

If you double the frequency of a photon, you double its energy. The highest possible energy photon is a gamma ray and the lowest is in the radio wave band, with radio photon wavelengths of many meters. Gamma rays have wavelengths that are a very very small fraction of a millimeter.

[Link – advanced]
Mathematically, the relationship between wavelength and frequency is represented by the equation $\lambda = c / \nu$, where λ (lambda) represents the wavelength, ν (nu) the frequency, and c the speed of light (a constant). λ is therefore inversely proportional to ν. Thus, the shorter the wavelength, the larger is the frequency and vice-versa.

The direct proportionality between photon energy and frequency is represented by equation (6-1),

$$E = h\nu \qquad (6\text{-}1)$$

where E and n represent the energy and the frequency, respectively, and h is a proportionality constant called Planck's constant.

Ch6/PhotonCharacteristics/p.2

Thus infrared photons, containing oscillating electric charges, are emitted from warm objects on the earth into the atmosphere at the speed of light. Let's now see how and why these photons might interact with greenhouse gas molecules.

Frequency and the greenhouse effect

Gaseous molecules are in constant motion in three different modes. The three modes all can be occurring in a freely moving gas phase molecule at the same time (Fig. 6-5). These modes are: translation (movement of the whole molecule through space in a straight line before colliding), rotation (about a central point), and vibration (cyclic back and forth motion). Gaseous molecules acquire the energy for *all three* of these modes of molecular motion through collisions with other gas phase molecules or atoms or through collisions with solids or liquids. Molecules can also acquire additional vibrational and rotational energy from the absorption of a photon. (High energy photons such as visible, UV, and gamma rays, in addition, excite an atom's or a molecule's electrons.) This leads to a basic question: Why should a photon interact with a molecule? There are a number of reasons. We consider the one that readily explains the greenhouse effect. (A warning: the following is a classical and not a more exact quantum explanation for the photon absorption process[link to vibration-rotation spectrum explanation]).

Fig. 6-5 Three different modes of molecular motion: translation, rotation and vibration. All three can occur at the same time.

Ch6/MolecularDipoles/p.1

Motions of all molecules: translation, rotation, and vibration

When the oscillation frequency of an infrared photon in the vicinity of a greenhouse gas molecule is such that it can "link with" with the frequency of motion of certain bonded atoms in a greenhouse gas molecule, all of that photon's energy can be absorbed by the molecule and the photon disappears. As these light wave packets move through space, their electric charges oscillate with a characteristic frequency. When an infrared photon passes close to a molecule, the photon can be completely absorbed by the molecule only when the frequency of the photon electric oscillations and the corresponding type of *electric* oscillations stemming from interatomic oscillations in the molecule are intimately linked.

If an infrared photon is absorbed by a greenhouse gas molecule, the energy of the photon is instantaneously transformed into additional molecular rotational and/or vibrational energy of the absorbing molecule. This newly energized greenhouse gas molecule is constantly colliding with other atmospheric molecules and can quickly distribute this newly acquired energy through collisions with other abundant atmospheric molecules such as O_2 or N_2. These energized molecules can distribute their energy to other molecules through further collisions. Consequently, the absorption of infrared photons by greenhouse gases increases the average energy of a collection of atmospheric molecules, which corresponds to an increase in the atmospheric temperature of that region.

Requirements for absorption of IR photon by greenhouse gas molecule

However, vibrationally and rotationally excited atmospheric molecules can also spontaneously lose part of this energy by emitting infrared photons. This new IR photon will be emitted in a random direction because of the molecules' constant rotation. A significant fraction of these emitted infrared photons are directed toward the Earth and, when absorbed at ground level, reheat the Earth. At last we have a molecular explanation of the greenhouse effect: short wavelength visible and short wavelength infrared photons from the sun are absorbed by the Earth, which emits infrared photons at longer wavelengths, which are absorbed and reemitted in random directions, absorbed and reemitted, etc., until they are lost to outer space.

Fate of the energy of the absorbed photon

Just as there are different colors corresponding to different wavelengths in the visible part of the spectrum, there are many different wavelength infrared photons. It is the longer wavelength infrared radiation from the Earth that is trapped by greenhouse gases, which can re-radiate other long wavelength infrared photons back toward the Earth, warming the Earth as well as other atmospheric gases. This continual trapping and re-emission results in a 30°C higher mean (average) global temperature than if there were no greenhouse gases present.

Figure 6-6 summarizes quantitatvely the processes responsible for the 31% of the sun's short wavelength energy reflected by the Earth and its atmosphere and the 69% of the sun's incoming energy that is absorbed and ultimately re-emitted by the Earth and its atmosphere in the long wavelength infrared region of the electromagnetic spectrum.

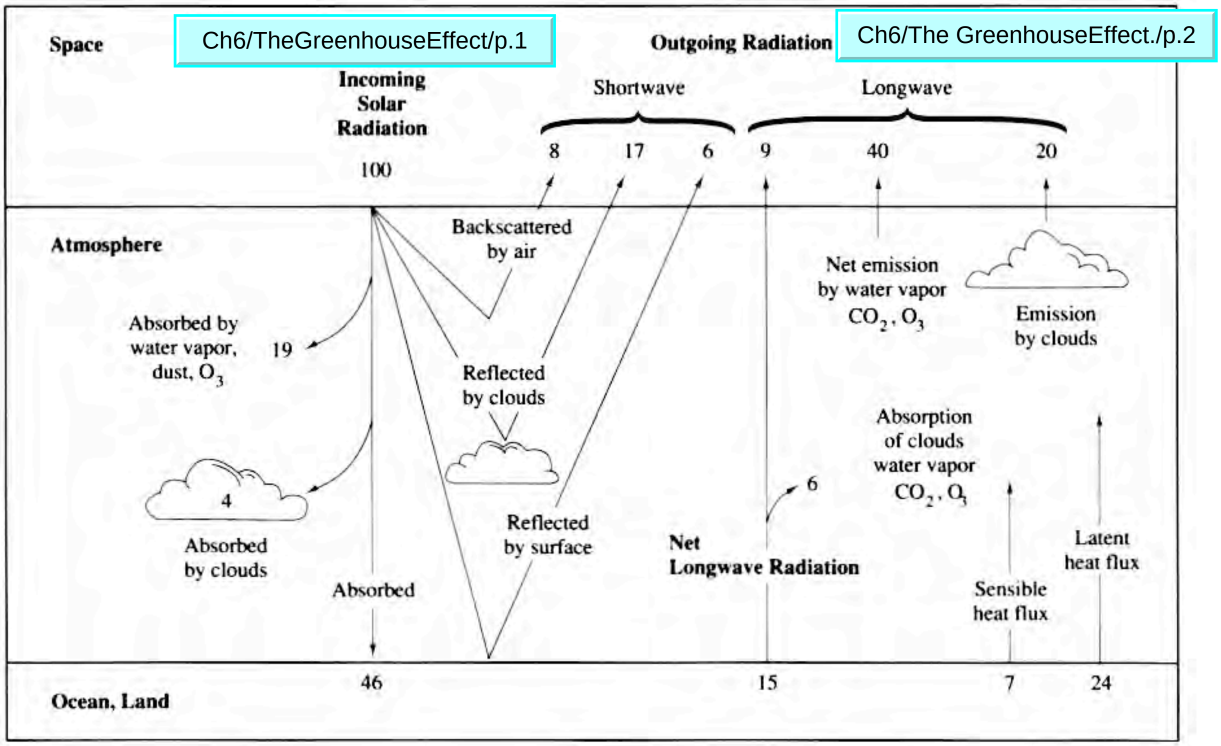


Fig. 6-6 Summary of the various processes taking place in the greenhouse effect. The numbers represent the percentages of the incoming sunlight energy in a particular process. For example, 69% of the incoming sunlight energy leaves the Earth as long wavelength infrared radiation. “Sensible heat” is warming of the atmosphere and “latent heat” is the heat carried by evaporated water (Schlesinger, Biogeochemistry, Academic Press, 1991, p. 22)

When the temperature inside an enclosed greenhouse is steady, the amount of heat energy escaping the greenhouse equals the amount of solar energy entering the greenhouse. But on a sunny day, this steady temperature is often uncomfortably warm. Similarly, for energy loss from the atmosphere to equal incoming energy from the sun requires that the atmosphere be warm. In other words, there has to be a sufficiently high temperature for the energy loss through the atmospheric ‘window’ to equal the incoming solar energy. If there is an imbalance in this radiative loss caused by increased greenhouse gas concentration, then the temperature of the Earth’s atmosphere rises until the balance is again achieved. That is, there is global warming caused by the presence of greenhouse gases.

Greenhouse gases

What is so special about greenhouse gases that they are able to absorb infrared photons? When valence electrons are polarized in bonds to form dipoles, as in the case of water, the natural rotations and vibrations of the water molecule result in molecular dipole rotation and vibration. These oscillating water dipoles have frequencies that are influenced by the oscillating frequencies present in certain infrared photons, making it a powerful greenhouse gas. Thus the water dipole interacts with the IR photon oscillating dipole and absorbs the IR photon. Each complex vibrational motion causes an oscillation in the dipole moment. Gaseous water molecules also rotate as well as vibrate with various frequencies. This wide range of rotation and vibration frequencies expands enormously the potential number of infrared photons of different frequencies that can be absorbed, since there are many rotational energies associated with each vibrational energy. Consequently a large number of changes in vibration-rotation energy of water molecules can occur through the absorption of infrared photons of many different frequencies, particularly those IR photons emitted by the sun-warmed earth.

Ch6/PhotonInteractions/p.1
Ch6/PhotonInteractions/p.2

Water is an important greenhouse gas

Consequently, water is one of our most powerful greenhouse gases. A good example of this power is the difference between radiative cooling (loss of IR photons from the sun-warmed earth) on a clear, dry night as opposed to a cloudy, foggy, or humid night. Dramatic temperature drops can occur on a clear night when there is low humidity because there are few gaseous water molecules and no clouds (condensed greenhouse gas) to absorb infrared radiation that escapes from and thereby rapidly cools the warm earth. The desert can have very cold nights! On the contrary, on a very humid or cloudy night, at least part of the IR radiation from the ground is trapped by humid air water molecules and clouds and re-emitted back to the earth resulting in the greenhouse effect and a much slower rate of cooling during the nighttime hours.

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Water vapor is a desirable greenhouse gas. The reason is that the *average* concentration of gaseous water in the atmosphere remains almost constant over a long time period. This is not the case with certain other greenhouse gases. The proposed danger of global warming and climate change lies in providing too many greenhouse gas molecules from anthropogenic emissions of excess amounts of CO_2 (carbon dioxide), CFCs (chlorofluorocarbons), CH_4 (methane), and N_2O (nitrous oxide) the major greenhouse gases. The atmospheric concentration of these gases has been increasing during the past century, with the exception of the CFCs.

Carbon dioxide is a greenhouse gas despite its being linear

Ch6/MolecularDipoles/p.2

It is difficult to reason why carbon dioxide should be such an important greenhouse gas, especially because unlike water, it is a “linear” and not a “bent” molecule. The *average* structure of CO_2 is indeed linear, but because the molecule vibrates, it can generate an oscillating dipole. Water is a bent molecule, and even when it bends back and forth during its vibrations, it never becomes linear. In contrast, the CO_2 molecule has no *net* dipole moment in its average linear configuration (Fig. 6-7). However, because of its various modes of vibration, the majority of which are asymmetric (lacking symmetrical movement), the CO_2 molecule generates oscillating dipole moments that can interact with a wide range of infrared photons with different frequencies. For this reason, it is one of the most important greenhouse gases and the most controversial because of its very rapid rise in concentration in the last century.

Asymmetric vibrations allow CO_2 to be a greenhouse gas

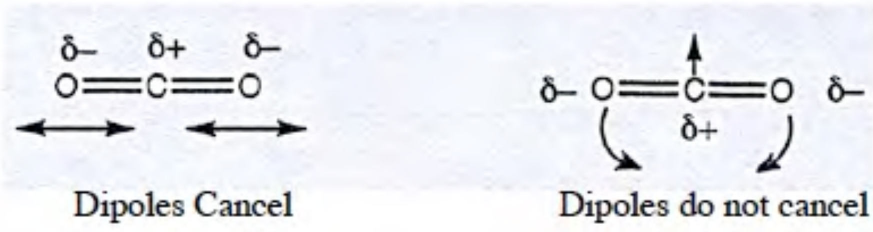

Fig. 6-7 Lewis structure of CO_2, with opposite dipoles canceling one another when the molecule engaged in a symmetrical vibration, and creating a net overall dipole when the molecule is bent during a "wagging" vibration.

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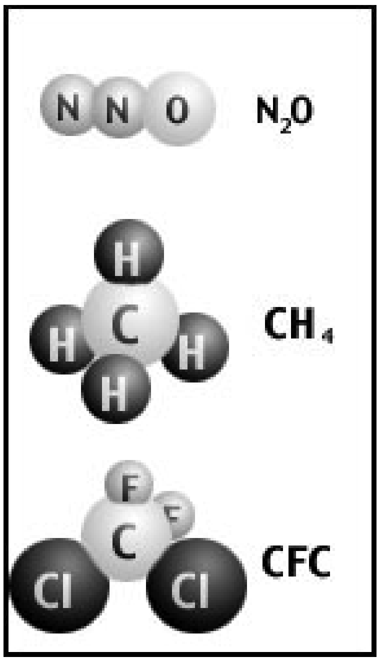
Nitrous Oxide, Methane, and CFCs are also greenhouse gases



Nitrous oxide (N_2O) has a permanent dipole moment and therefore is not a symmetrical molecule. Experimental evidence indicates that one of the nitrogen atoms in N_2O is located between the oxygen and the other nitrogen atom in a linear arrangement (i.e., NNO). Again, nitrous oxide is a greenhouse gas because its oscillating motions create an oscillating dipole that interacts with the oscillating electric dipole of infrared photons.

Methane is a greenhouse gas despite being symmetrical

Methane is depicted on the left as a symmetrical molecule. It has no *net* dipole moment in its average configuration, but because of its many asymmetric modes of vibration it has oscillating dipole moments and is thus an important greenhouse gas. Because it has more atoms than carbon dioxide, methane has a larger number of vibrational modes and is a stronger absorber of long wavelength infrared radiation per greenhouse gas molecule than carbon dioxide.

CFCs are strong greenhouse gases

Almost all CFCs have permanent dipole moments because of the high electronegativities of chlorine and fluorine in comparison with carbon. In many of their vibrational or rotational motions, there is an oscillating dipole frequency of the CFC that can interact with infrared photons of many different frequencies. Therefore, these CFC molecules are *very* effective greenhouse gases. CFCs are up to 7,000 times more effective infrared absorbers *per molecule* than a single molecule of CO_2.

Ch6/TheGreenhouseEffect/p.5

We all know not to touch a glowing red electric stovetop heating element. If our hand approaches a stovetop element that is not glowing, our hand approaches the "red hot" element cautiously and "feels" if it is still hot. If it is still hot, there is no *visible* radiation that emanates from the heating element, only infrared radiation (IR) A white hot Sun and a warm heating element both emit photons. The spectral wavelengths of these two objects are quite different. The Earth emits IR photons of even longer wavelengths. Click here for a more advanced examination of this topic.

——————————————Advanced Material——————————————

Solar and Earth radiative temperatures and greenhouse gas spectra

We know the Sun as a radiative body. That is, it gives off radiation that heats us and provides the energy to make our lives possible. Most of us have heard the term "red hot", for example, as in a ret hot electric stove heating element. Some of us have heard the term "white hot" from seeing pictures of the inside of steel furnaces or from welding processes, where one needs eye protection to protect from UV given off from the high temperature welded object. When a red hot object such as stove heating element cools down, we can still feel the heat from the hot object without touching it because of the IR photons being emitted. If we take the UV visible and IR **spectra** (number of photons per unit time plotted vs. wavelength of the radiation) of each of these heated objects, we note an interesting shift in the peak (⋆) of the maximum number of photons in these plots (Fig.6-8).

As the temperature of the object increases, the maximum shifts to shorter wavelengths from the infrared (hot, but not visibly hot object) through the visible (red hot object), then the hotter (white hot object) with increased temperature. Experiments on various objects have shown that this is a general tendency for *all* objects, regardless of their composition. Physicists have hypothesized a fictional model object, but based on experimental studies, called a **blackbody**, black because it absorbs completely all photons, reflecting none. This blackbody is then heated, giving off radiations with different spectra as its temperature is increased, again colorless through red through white hot, increasing its UV output. Fig. 6-8 is the calculated theoretical spectrum, called a Planck curve, of such an object at three different temperatures. The temperature (T) in this figure is given in **absolute temperature** units, where T = t (ºC) + 273. The shift in the peak of the spectrum can be seen to shift through the visible and, at the highest temperature, resides in the UV.

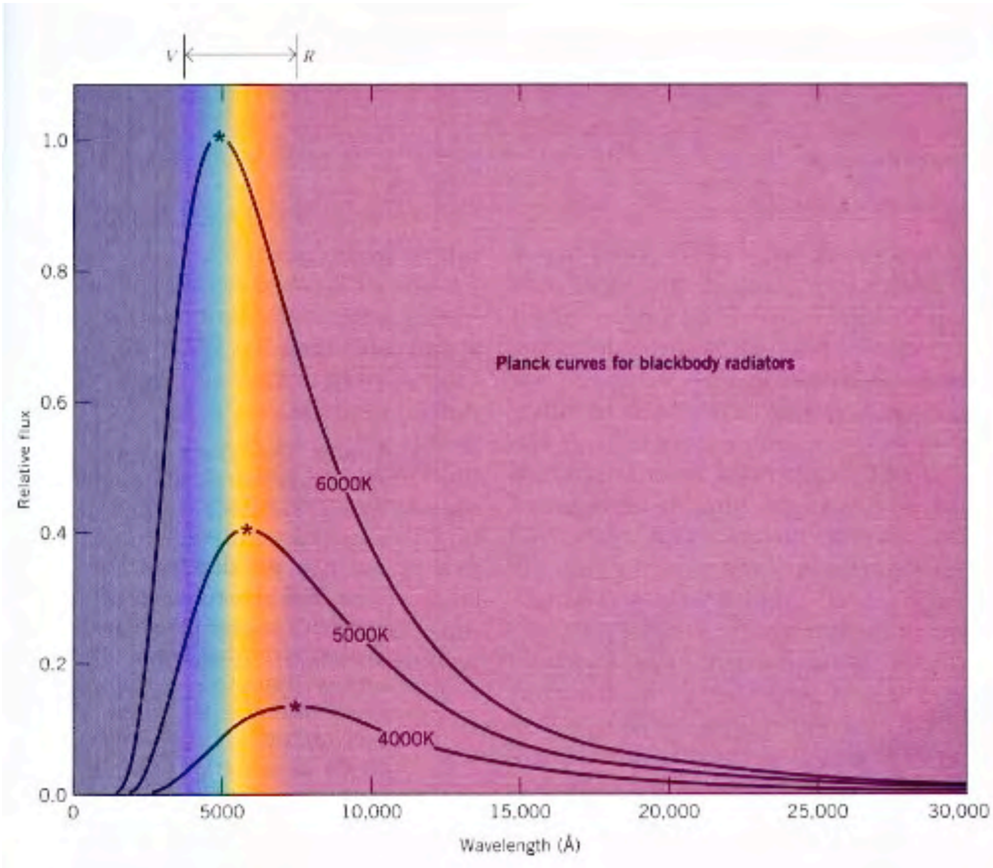


Fig. 6-8 Theoretical blackbody spectra calculated from an equation derived from experimental studies of objects approximating bodies that absorbed all radiations but then radiated the absorbed energy as a blackbody would. The top arrows designate the visible region of the electromagnetic spectrum. To the left of this region is the ultraviolet and to the right is the infrared. The wavelength is given in Angstrom units, where 1 Å = 1×10^{-10} meters.

The Sun is a very hot body. It's temperature has been estimated from such blackbody considerations to be ~6000 K (with absolute temperatures, the º symbol is not used). Thus, if we take a spectrum of the sunlight from a satellite outside the Earth's atmosphere, we would expect to see a spectrum similar to the 6000 K spectrum illustrated by the dashed black line shown in Fig. 6-9.

The solid brown curve in Fig. 6-9 is the experimentally observed solar spectrum in space with the above calculated dashed Plank spectrum superimposed on the experimental spectrum. The fit is fairly good, although the experimenal spectrum is not as smooth as the calculated one. This is probably because the space between the Sun and the Earth is not a complete vacuum and some of the light, especially in the

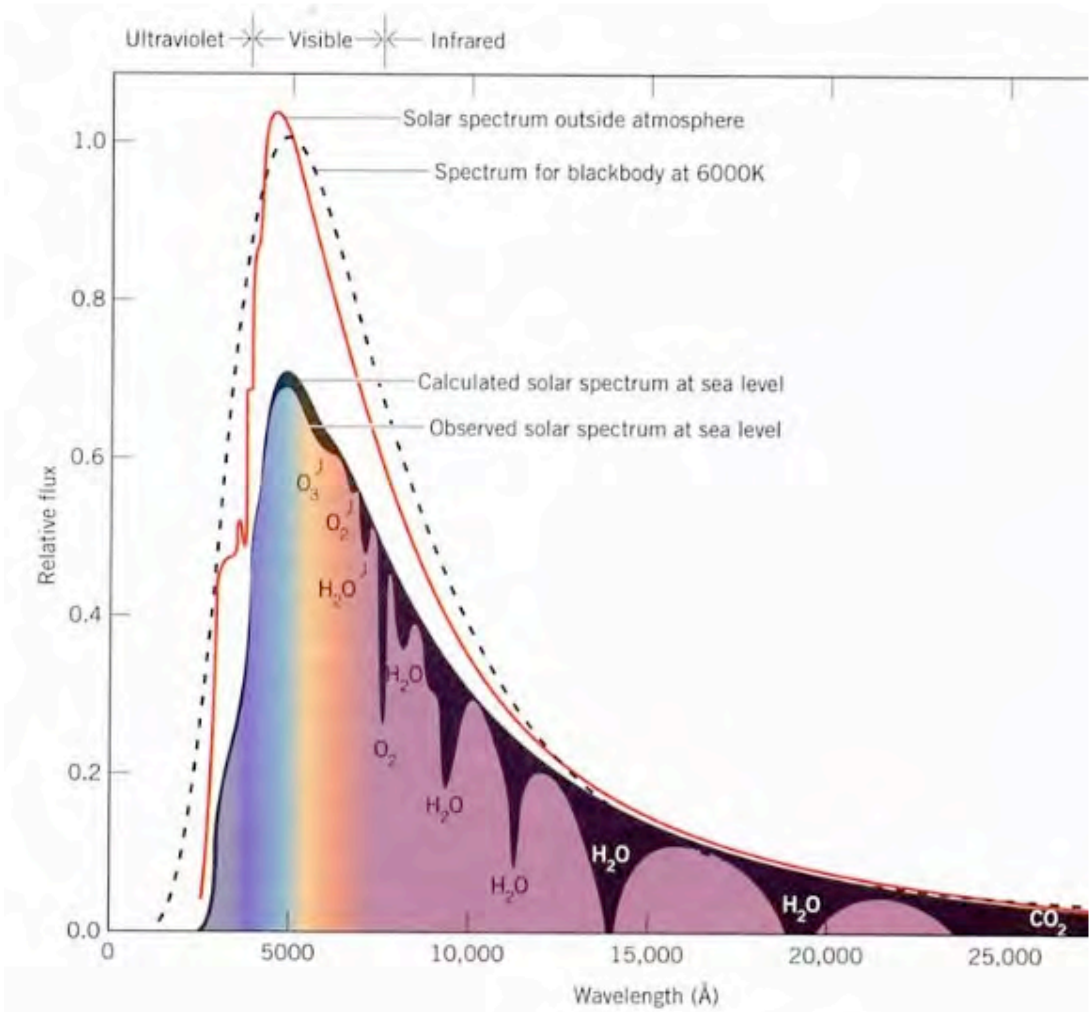


Fig. 6-9 Solar spectra outside the Earth's atmosphere and at the Earth's surface. The black areas represent the calculated missing solar photons that are absorbed by the inidcated atmospheric molecules in the Earth's atmosphere. The wavelengthis given in Angstrom units, where 1 Å = $1x10^{-10}$ meters. P.280 Zeilik Astronomy John Wiley 1994

solar UV emission is absorbed by molecules in this space. The smooth bottom curve, not including the black parts, is what the solar spectrum is calculated to look like at sea level.

Note that in Fig. 6-9 the dipping black areas are actually are measures of the infrared spectrum of all the molecules in the Earth's atmosphere. This can be demonstrated experimentally (Fig.6-10) with individual atmospheric components, which is why the major molecules responsible for the IR absorption regions or bands can be assigned as they are in Fig. 6-9.

If the Sun is a radiating blackbody. Why, then, can't the Earth also be thought of as a radiating blackbody, just as a cooling stove heating coil radiates heat? If we take the spectrum of the radiation coming from the heated Earth, we find that, without an atmosphere, the blackbody radiation temperature is –18ºC (273–18 = 255 K). But the Earth doesn't radiate visible light, only reflected visible light from the Sun, for example, from clouds, snow and ice. Thus its radiative spectrum is entirely in the infrared. We have seen this spectrum before in Fig. 6-2 (link). The infrared spectrum derived from the incoming absoprbed solar IR photons is now relevant with respect to the outgoing exclusively IR photons radiated by the Sun-warmed Earth. However, because of the different peaks of the sunlight and the earthlight spectra, we don't need to worry about certain regions of the IR because these are emitted by the Sun but not the Earth. The region in Fig. 6-10 labeled "atmospheric window" represents the region responsible for the greenhouse effect. The individual greenhouse gas contributions to the overall greenhouse effect can be seen in each of the shaded regions of Fig. 6-10. Water vapor and carbon dioxide can be seen as the most intensely absorbing greenhouse gases of these compounds.

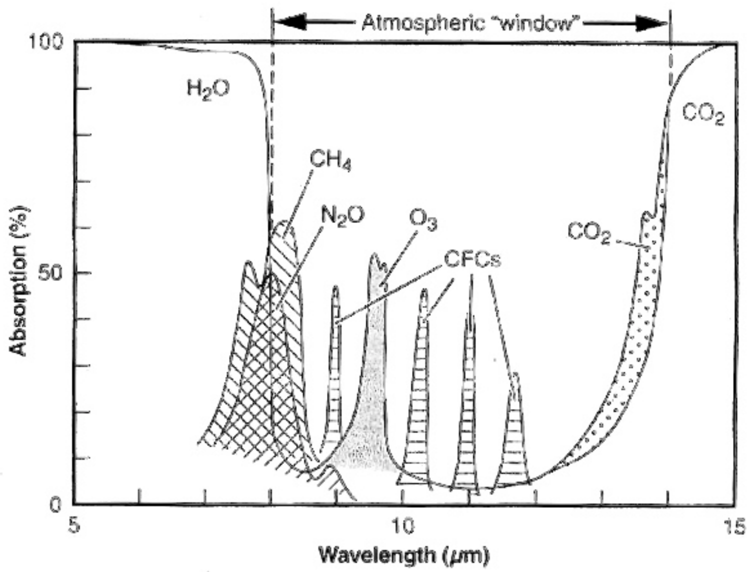


Fig. 6-10 IR, spectra of principal atmospheric constituents in the "atmospheric window" region. The relative sizes of the absorption bands are illustrated. 1μm = 1 micrometer = 1x10^{-9} meters.Turco p 338

——————————— end of advanced material ———————————

The greenhouse effect is very closely tied with visible and infrared spectra. Visible because the incoming solar radiation is mainly in the visible and the UV. The spectrum of sunlight before it enters the atmosphere is rich in UV, but the highest energy UV is filtered out by O_2 and O_3. Not all of the visible light gets to sea level, despite the fact that atmospheric gases are transparent. Some visible light is scattered by clouds and some blue light is scattered to make the sky appear blue. Significant spectral bands of the incoming solar IR light are absorbed by greenhouse gases, warming the atmosphere from incoming solar radiation. However, these same greenhouse gases also absorb the outgoing infrared radiation from the Sun-warmed Earth to further heat the atmosphere. Thus there are two infrared sources for the warming of the atmosphere, one from incoming IR photons from the Sun, the other from outgoing IR photons from the Earth.

Why aren't oxygen and nitrogen greenhouse gases?

If the atmosphere were to consist of only nitrogen and oxygen, all of the IR emanating from the sun-warmed Earth would escape into space and the world would be much cooler. Why don't these two molecules absorb IR? From the above discussion, we have seen that IR photons are absorbed only when they encounter a molecule that has an oscillating dipole. Certainly O_2 and N_2 molecules oscillate like all other gaseous molecules. They vibrate and rotate, but because they have no net dipole at any time during either of these motions, they cannot absorb an IR photon. Hence they are transparent to IR photons. They are also colorless gases and therefore do not absorb visible light photons. Both O_2 and N_2 absorb UV photons, the absorption by O_2 being responsible for the formation of the ozone layer. These molecules absorb high energy UV photons because the UV photon's oscillation stimulates oscillation of electrons within the molecules. Thus, after absorption of the UV photon, the molecules are electronically excited. In addition they are usually also rotationally and vibrationally excited and the gaseous molecules are likely to dissociate, as is the case for electronically excited oxygen and ozone.

The question "What is a greenhouse gas and what is the greenhouse effect?" has been answered in detail in the above sections. The question arises, are these small concentrations of atmospheric greenhouse gas the only causes of global climate change? Are there other forces that induce climate change? If so, how important are they in relation to the climate forcing power of the greenhouse gases?

What Are the Possible Causes of Global Climate Change?

The remaining section of this chapter deals with a question that is more difficult to answer and has engaged many thousands of scientists around the world: "Are 'global warming' and 'global climate change' caused *exclusively* by increasing concentrations of greenhouse gases?" The short answer is is "No". However, the question can be phrased differently: "Are increasing concentrations of greenhouse gases *the most important* cause of global climate change?" The answer given by the scientific community engaged in climate change research is overwhelmingly "Yes."

Let's clarify the definitions of two critical terms that are being used quite heavily in the press and in this chapter. Warming that is larger than the range of the Earth's natural temperature variability is designated as **global warming**. Abnormal global weather patterns associated with increased greenhouse gas concentrations and the resulting warming are designated as **global climate change**.

Atmospheric and meteorological scientists are attempting to answer the following questions. Have human activities affected past weather trends and will they affect the future climate and temperature of the Earth in undesirable ways? Are increasing greenhouse gas concentrations the cause of past temperature and climate anomalies? Will the Earth heat up in the future even more rapidly than at present? If so, by how much and when? What will be the consequences? We explore below various attempts by scientists to answer these questions. At present, some of these questions have no unequivocal answers. Some of the suggested answers are subject to challenge because of the assumptions needed to answer the questions or because of the lack of sophistication of models used to predict the future weather trends.

Global temperature trends

However, there is general agreement among scientists that both the concentration of greenhouse gases and average global temperatures have increased during the past century. There is also a broad concensus among those scientists who are actively engaged in research in the scientific field of climate change that human activities have indeed caused increased global temperatures and influenced the world climate in the recent past. Further, they predict that unless measures are taken to reduce the human production of greenhouse gases, the probability of undesirable, perhaps even catastrophic, future changes in the Earth's climate is very high.

How can this be when the local climate doesn't seem to be changed that much or even near a crisis point? The answer is complex and involves climate terms that need to be defined and understood. The most important of these terms are: forcings, climate sensitivity, feedback, and tipping points, defined below**.**

Climate forcing and forcing agents

What is forcing? It has to do with the planet Earth's energy balance between incoming solar radiation and outgoing reflected sunlight and infrared radiation emitted by the Earth. This, in turn, has to do with molecules and events that cause perturbations in this energy balancing processes. For example, there is external forcing if the Sun were to suddenly, or even slowly, to increase its radiation output. This would force the Earth's climate to change because of the increased radiation energy absorbed by the Earth. The forcing agent would be the Sun. The *change* in solar output and the resulting increased Earth radiation output defined as **climate forcing**. There is good reason to believe that solar radiation forcing is associated with the cylic nature of the ice ages throughout the Earth's history. However, based on calculations of the amounts of these solar energy input changes, scientists have to postulate **feedbacks**, factors internal to the climate system that can amplify or damp the external forcing. Solar forcing is a good example of external forcing.

The internal forcing agent in which we are most interested is in response to the class of molecules known as the greenhouse gases. The most important of these is CO_2. The climate forcing is the warming of the Earth's atmosphere because of the increase in greenhouse gas concentration.

Consider the situation in which there is as much solar energy per year entering the Earth's atmosphere as is being emitted in that same year as the sum of the reflected visible and infrared radiation emitted by the Earth itself. This is, from an energy point of view, a nicely balanced energy system at equilibrium. The rate of heat energy flowing in (100%) equals the rate of heat energy flowing out (100%). See Fig.

6-6 for the details of the process.

Now, suppose we suddenly add to the atmosphere a very large amount of the greenhouse gas CO_2. This gas absorbs all of the infrared radiation emitted by the Earth. At the moment this happens, the Earth's energy balance is completely upset. No infrared radiation is being emitted by Earth to outer space. The bottom layers of CO_2 are warm because they completely absorbed the Earth's IR radiation. The upper layers of atmosphere still radiate IR to outer space and become cooler. However, the warm bottom layer CO_2 emits IR radiation in random directions. Roughly half of this heat is directed back toward the Earth, but on its way, most of it is absorbed by other intervening CO_2 molecules. These molecules, in turn, emit IR radiation in random directions and other CO_2 molecule absorb it, re-emit it, etc. This ping-pong IR emission-absorption-emission transfer of energy continues until the IR photons reach the upper atmosphere where there are fewer CO_2 molecules and finally some of these IR photons escape into outer space. However, these IR photons are being emitted in a much colder region of the atmosphere and are of lower energy, so less energy is being emitted than if there were no CO_2 in the atmosphere. The energy balance is still upset. Meanwhile, as the Sun continues to pour energy into the Earth's atmosphere, the Earth's IR emissions continue to warm the CO_2 and surrounding atmosphere in successively higher layers. This emission continues to warm the CO_2 until the amount of IR photon energy being emitted per hour mainly near the top of the atmosphere exactly equals that coming into the Earth from the Sun per hour. At this point the atmosphere stops warming and the climate has now been stabilized again following the forcing. The internal forcing agent, the sudden change in CO_2 concentration, forced the Earth's climate to change its atmospheric energy balance.

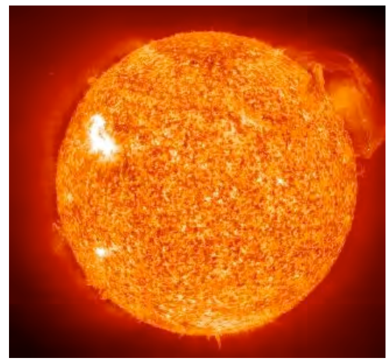
The above process initiated by the introduction of CO_2 is called **climate forcing**. The suddenly added CO_2 is called **forcing agent**, that which causes a temporary energy imbalance in the energy input-output equilibrium. In this instance, the forcing has caused increased temperature, and the forcing is designated as positive forcing.

What are the other forcing agents? All greenhouse gases such as methane, nitrous oxide, CFCs, and ozone are positive forcing agents. The Sun is a positive forcing agent if its output increases and a negative forcing agent if the Sun's output decreases. One recently designated important positive forcing agent is black carbon aerosols, discussed in Chapter 5, that absorb sunlight and warm the atmosphere.

There are several negative forcing agents that cause cooling rather than warming. One is any aerosol that reflects sunlight, such as the sulfate aerosols from oxidized SO_2. These are thought to be partially responsible for the flat average global temperature of the 1970s before the removal of SO_2 from coal plant smokestacks. Another negative forcing agent is any process that produces increased numbers of reflective clouds (see below). In some cases, agents can act either as positive or negative forcing agents, depending on circumstances. For example, consider the case of land cover and/or use. When forests are replaced with crops of short stature, forests absorb more incoming sunlight than more reflective crops. Such a substitution would change the energy balance of the incoming vs. outgoing sunlight. On the other hand, substituting green parkland for a parking lot would probably alter the energy balance in favor of cooling the climate, at least locally.

Variations in solar radiation intensity

Solar cycles are well known, although the reasons for these are not. Since 1750, the Sun has undergone a cycle of sunspots, solar radiation, solar flares, and radio wave output, all with the same cyclic increase and decrease every ~11 years within an added ~22 year cycle. Not only do these cycles affect our stratosphere chemistry, because of the fluctuation of solar UV, it affects the Earth's weather and climate in the troposphere. Increases in solar intensity increases the amount of ozone in the stratospheric ozone layer. In addition, in those susceptible locations, increased solar intensity increases the amount of daytime smog. However, ozone is also a greenhouse gas and these increases in ozone concentration trap more of the Earth's outgoing IR radiation.



The magnitude of this effect on global temperature is calculated by atmospheric scientists to be smaller relative to that caused by warming from increasing concentrations of other greenhouse gases such as CO_2. Recent analyses of natural factors such as solar variation and volcanoes conclude that the Sun contributed only about 10% of surface warming in the last century. There have been claims of an amplification of these small solar variations into large effects, but there have been no peer reviewed scientific papers to back up these claims. Temperatures have risen during recent dips in solar energy input. Also, winters are warming more rapidly than summers and overnight minimum temperatures increased more rapidly than daytime maxima – the opposite of what would be the case if the Sun were causing the warming.

Aerosols and black carbon

As indicated in Chapter 5, the sulfur dioxide from burning sulfur-containing coal is oxidized ultimately to sulfuric acid in the troposphere. This acid is partially neutralized by metal oxides in atmospheric particles, yielding suspended solid metal sulfate particles. These sulfate particles as well as other types of suspended particulate matter can reflect sunlight away from the Earth and reduces the amount of sunlight arriving at the surface of the Earth. Thus sulfate particulates tend to cool the Earth. This is one case where an air pollutant reverses the effect of another pollutant, carbon dioxide, a greenhouse gas that tends to warm the atmosphere. In addition, there are other airborne particulates such as volcanic ash and wind-blown dust that reflect sunshine.

However, there is another type of particulate that is found to be a significant player in global warming, that contained in so-called "brown clouds," already considered in Chapter 5 (link). Although these clouds contain some reflective sulfate and ash particles, they also contain nanometer to micrometer-sized black soot particles that efficiently absorb sunlight and do not reflect it. Research on these brown clouds concludes that their net effect is to increase global warming. It is also clear that with a relatively focused program aimed at increasing the efficiency of fuel oxidation, a major part of this warming problem can be mitigated with major improvements in health as a bonus. This is because these small soot particles contaim harmful adsorbed chemicals that are absorbed into the bloodstream after being inhaled into the lungs.

The aerosols are part of a "Faustian Bargain" according to James Hansen. As we burn coal containing sulfur, we produce two gases SO_2 and CO_2. As you know, CO_2 causes warming. The SO_2 produces an aerosol that causes atmospheric cooling that helps to counteract the CO_2 warming. However, if we stop buring coal or are able to eliminate the SO_2 air pollutant, we also stop the production of the cooling aerosols. However, the CO_2 remains in the atmosphere for centuries and continues its warming. Hence, the Faustian Bargain with the unpleasant ultimate consequences.

Land use and climate

Vegetation both responds to climate change and has important climate effects (through albedo, increasing the efficiency of water evaporation from soil, and storage of carbon). Effects of the first two (albedo and latent heat fluxes) can be as important (and on a regional scale are more important) than the effects of CO2. For example, large scale planting of forests to take up CO2 will have effects on the availability of local fresh water supplies. Planning how to manage land needs to take all of these factors into account.

Volcanic eruptions

Major eruptions of volcanoes can significantly alter the weather and temperature on a global scale. This occurs because huge quantities of the gases and particulates ejected by the volcano are thrust into stratosphere, where they are stratified and circulate around the globe, sometimes for periods up to several years before dissipating. Both the volcanic ash particulates and the secondary sulfate particles reflect incoming sunlight back into space, thus lowering the amount of energy reaching the Earth's surface.

The stratospheric eruption of Mt. Pinatubo in the Philippines in June 1991 was the largest volcanic eruption since the eruption of Mt. Krakatoa in 1883. The ash and particles formed from chemical reactions of the resulting gases probably did directly affect global warming by lowering the global temperature. This is most likely due to sunlight being reflected from the particles of ash and from the sulfate particles formed in the atmosphere from

the oxidation of volcanic sulfur dioxide gas. Scientists are reconsidering the role of volcanic eruptions in triggering ice ages because of recent findings of volcanic ash in ice cores. The Mount Pinatubo eruption (photo right) first heated the stratosphere to very high temperatures and then cooled it over a two-year period to well below average temperatures. The reason for this oscillation is not completely understood, although it may be connected with a loss of stratospheric ozone induced by the aerosols from the volcanic eruption.

We have listed above the major agents that are able to perturb the Earth's climate. Which of these agents are the most influential and destabilizing?

What are the critical forcing agents?

Which are the most important forcing agents? That is, to what forcings is climate most sensitive. An interesting empirical model to fit current temperature trends has been created with just four variables (Fig 6-11B - bottom graphs): Greenhouse gas concentrations, El Nino-Southern Oscillation Pacific Ocean equatorial temperature anomalies (Link), volcanic aerosols, and the incoming solar intensity. Fig. 6-11A (top graph) shows the very good fit between model and fine structure of the data. Except for some extreme temperature spikes, the model fits nearly all of the temperatures oscillations both qualitatively and quantitatively. The ability to closely model the general fine structure in the experimental data trends is striking. In the bottom graph of Fig. 6-11B, the "Anthropogenic effects" represent the steady buildup of greenhouse gases from human activities.

The excellent fit of the data in Fig. 6-11 does not *prove* anything! It proves that if one fiddles with the data, one can achieve a nice fit. There are many correlations in science and in life that are completely coincidental. However, this fit plus many other theoretical and similar types of experimental studies allows scientists to make hypotheses that can be further tested in other more sophisticated models. The main conclusion from this study is that there is no way in which the data in Fig. 6-11 can fit temperature data without including the influence of increasing greenhouse gas concentrations. This is one of the many different clues demonstrating importance of greenhouse gas concentration increase as a very sensitive contributor to global warming.

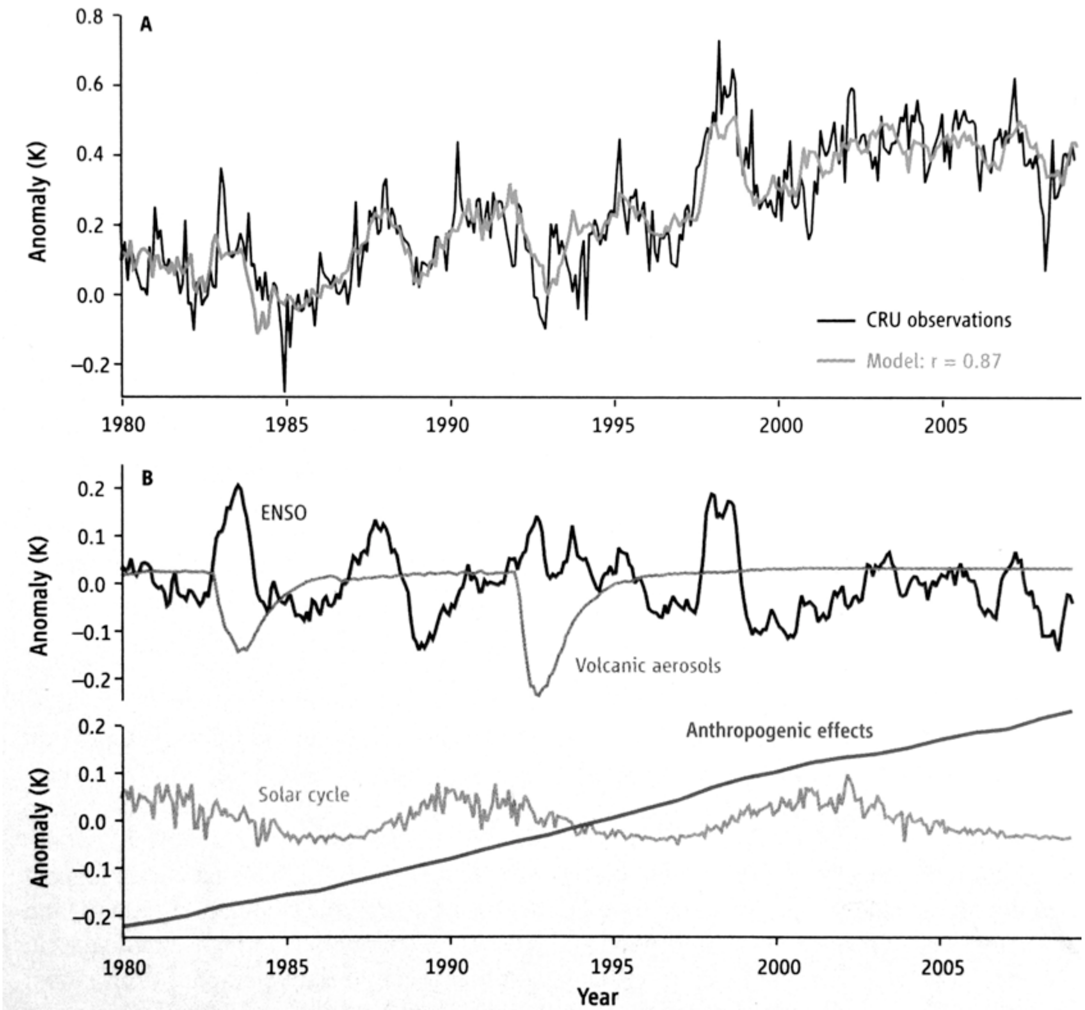


Fig. 6-11 Empirical model of global temperatures with only four inputs: ENSO (El-Nino weather pattern), volcanic activity, solar intensity, and greenhouse gas concentrations. CRU observations are data indicative of increases and decreases in global temperatures for different times. The model takes the four data sets in the B section of the graph and gives each set a different importance by multiplying it by a different sensitivity factor and adding these to give the light gray data graphed in the upper A section. These model data can then be compared with measured temperatures. Science, Vol 326, 18 Dec, 2009, p.1652.

Climate sensitivity, feedbacks, tipping points, and inertia

We have seen the different types of climate forcing agents and now explore the potential quantitative aspects of such forcing. That is, if a forcing is positive, how sensitive is the forcing to the type and extent of the forcing and how fast does the temperature rise? In short, how sensitive is the climate to different forcings? This sensitivity is twofold: how much and how fast will the change take place? We will find that most naturally-induced forcing is relatively slow, sometimes in the time span of thousands of years. On the other hand, some natural events can be devastatingly fast, as in the case of negative forcing induced by meteoroids and volcanoes. Human-induced forcings, such as in greenhouse gas buildup is relatively fast in comparison with natural forcings. In general, forcing that produces warming is faster than forcing that produces cooling.

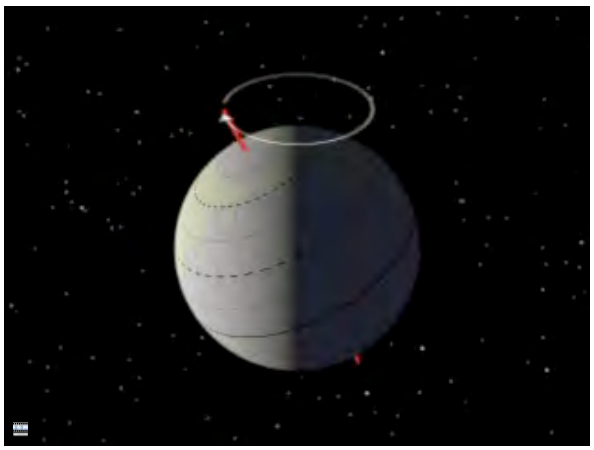
Feedbacks

Forcings drive climate change. On the other hand, feedbacks determine the magnitude of the climate changes resulting from the forcings. What is a climate change **feedback**? Feedback is the process in which changing one quantity changes a second quantity, and the change in the second quantity in turn changes the first. For example, consider water vapor feedback. Warmer air holds more water vapor, which is a greenhouse gas. Thus, a higher concentration of water vapor, that is a higher humidity, leads to a greater greenhouse effect with resulting higher temperature. This higher temperature vaporizes more water vapor, which leads to an even higher greenhouse effect, which raises the temperature even higher, which… i.e., this is a positive feedback. However, this water feedback effect will less sensitive as the water vapor content of the atmosphere increases. One reason is that for a given temperature, the atmosphere can only hold a certain amount of water vapor. Beyond this amount, the vapor saturates and condenses into precipitation, which absorbs a much smaller percentage of the outgoing IR. That is, the water feedback tends to saturate. However, there is a further feedback, especially in the tropics, of increasing temperatures driving the water vapor to higher levels in the troposphere, thereby increasing the water vapor greenhouse effect because of the increased total water vapor content of the atmosphere.

On the other hand, the absorption of IR photons emitted from the Earth is more sensitive to increasing concentrations of CO_2. Increasing concentrations of CO_2 do not saturate and form liquid CO_2. Therefore CO_2 is capable of having larger concentration feedback effects when CO_2 concentrations increase by a certain percentage than when water vapor concentrations increase by the same percentage. That is, increasing CO_2 concentrations at many different CO_2 concentrations increases the amount of IR absorbed from the Earth's emissions. In some cases, there is a competition between two feedback systems, for example between negative ice sheet feedback cooling and positive greenhouse gas warming (see below).

What role does inertia play in climate science? The ocean plays a critical role as a sink for soaking up excess heat and CO_2 and it will be able to handle both of these – if given time. However, unfortunately, the rate of uptake of heat and CO_2 is one of the main sources of inertia, that is, slow response time in climate change dynamics. Inertia can be tricky and may show up early in a response but be overcome by other unexpected consequences, as in the case of accelerating destruction of ice sheets. Certainly, the human element in climate change has its share of inertia. The political and economic will to abandon a fossil fuel-based energy system is a prime example of inertia.

We now examine the detailed scientific evidence for past climate forcings, climate sensitivity and inertia, starting with processes that control climate and the long term climate records of the past for explanations of climate change processes.



Correlations of greenhouse gases and temperature

If we take a very long range perspective, say 80 million years, the global temperature of the Earth has apparently cooled on the order of 5 °C over this period. According to geologists, when dinosaurs became extinct about 65 million years ago, the Earth was ice-free. Between 15 and 35 million years ago, a permanent Antarctic ice sheet formed. In the last million years, the Earth has experienced eight ice ages, each lasting about 100,000 years. The last Ice Age was 18,000 years ago. Each of these ice ages was briefly interrupted by an "interglacial" period. We are currently in an interglacial period. These ice ages are caused by a wobble of the Earth's axis that is much like that of a wobbling top. (Search UTube for "top precession" or "Earth precession and open the figure at the top of the next page by double clicking the figure, if you are able to, on your computer.)

Correlations from ice core studies

Much progress in understanding long term trends has been made by studying the chemical identity and amounts of gases in trapped gas bubbles in ice cores from different cold regions of the world. As snow piled on top of snow, gases from the then-current atmosphere were trapped within the snow. Increasing weight of the snow above turned the deeply buried snow into ice and the trapped atmosphere migrated into bubbles as ice formed. Scientists have been able to carefully release this trapped gas and analyze it for its chemical content. Different ice layers are dated and analyzed.

Studies of deep ice cores taken in the Greenland ice sheet and in Antarctica have provided much of this evidence (Fig. 6-11). Data from more recent ice layers in these studies agree with measurements obtained by various other experimental methods during the same time periods. This data overlap gives confidence that the trapped bubble data are reliable and accurate. Accurate time resolution is possible in the analysis of these ice cores, with yearly cycles clearly detectable in some cases.

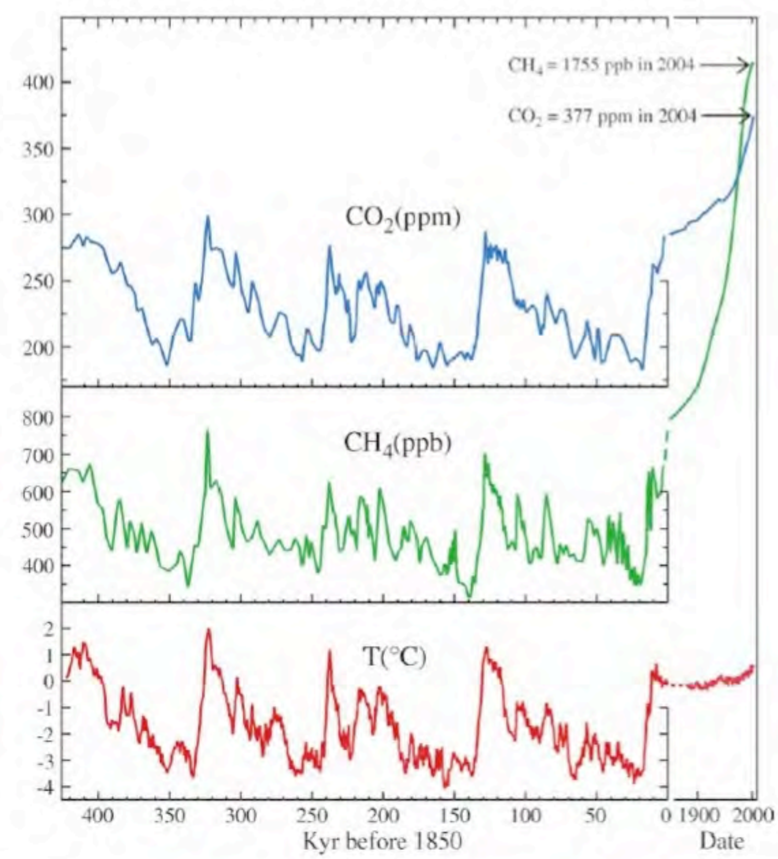


Fig. 6-12 Data from Antarctic ice cores for CO_2, Antarctic temperature, and methane covering the last four glaciation cycles. "ppm" signifies parts per million. "0" on the lower right axis represents the "modern" values (1850) on the highly expanded right scale. Note the sharp increases following 1850. The 2010 values for CO_2 and CH_4 have both increased from the 2004 values shown above (389 ppm for CO2 and 1800 ppb for CH_4).

Data are now available from much earlier times than those shown in Fig. 6-12. These show at least 8 interglacial warm periods similar to our own during a period of 800,000 years. Temperatures during these periods are calculated from analyses of the isotopes of H and O in the ice. Water in the ice deposited during very cold glacial periods has less of the heavier isotopes (H-2 and O-18) than in the warmer hydrogen and oxygen periods. In vaporizing water, the lighter isotope water molecules break bonds more easily and escape from the water surface, especially so at elevated temperatures. When this escaped water forms snow, water with lighter isotopes is foud in greater abundance the higher the water temperature. Thus, ratios of light to heavy isotopes provide a relative temperature signal for the ice core data. In nearly all of the data, there are correlations among the concentrations of the greenhouse gases CO_2 and CH_4 and estimated temperatures over the past 400,000 years.

The cycles of increasing and decreasing temperatures are followed fairly closely by the cyclic increases and decreases in methane and somewhat more approximately by carbon dioxide. These data suggest that there was a direct coupling between atmospheric carbon dioxide and methane concentrations and climate during the last 800,000 years. The reason for this close correlation is not completely understood, although it is probable that the warmed oceans following glaciation periods released large amounts of carbon dioxide. CO_2 liberation upswings lag about 200 years behind upswings in temperature. The moden day analogy is the release of carbon dioxide bubbles from warmed carbonated (CO_2) beverages. However, the role of biological species on land and in the sea in taking up this excess carbon dioxide is not clear.

The 2010 value for atmospheric CO_2 concentration is about 40% higher than any peak CO_2 concentrations during the last 400,000 years. The corresponding 2010 increase in CH_4 concentration is about 180% higher than any previous peak CH_4 concentration.

More recent concentrations of the most important greenhouse gases are shown in Fig. 6-13. The trends are steadily upward for both CO_2 and N_2O, with hints

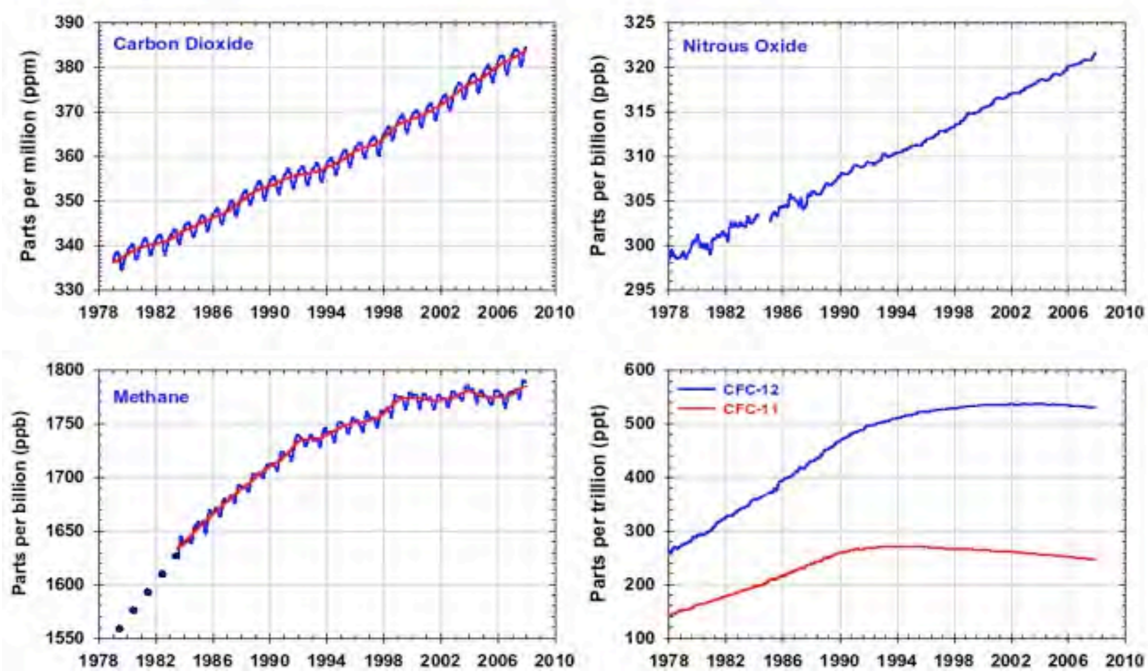


Fig. 6-13 Concentrations of important greenhouse gases in the late 20th and early 21st century.

of a leveling for both CH_4 and the most important CFCs (chlorofluorocarbons). CO_2 levels in 2010 were 389.7 ppm, as anticipated by extrapolating the graph for CO_2 in Fig. 6-13. However, CO_2 emissions from burning of fossil fuels in 2008 were 40% higher than those in 1990, indicating that there was, at least in 2008, no lettup in the dependence on fossil fuels. There was at least a three-fold acceleration in fossil fuel burning in the last several decades.

The persistent rise of both carbon dioxide and nitrous oxide in Fig. 6-13 are troublesome. The sources of carbon dioxide are clear whereas the mitigation solutions are not. Nitrous oxide (N_2O) is produced both naturally and from anthropogenic sources, the most important of which is land use. Agricultural soil management, animal manure management, sewage treatment, mobile and stationary fossil fuel combustion, and several industrial processes all produce N_2O. Heavy use of synthetic nitrogen fertilizers in crop production result in more N_2O. Microbial action in wet tropical forests also produce N_2O, which has an estimated atmospheric lifetime on the order of a hundred years.

Recently an important positive feedback has been confirmed that had been ignored earlier when it was assumed that the net global water vapor content was assumed to be constant and independent of global temperature. Instead, it is found that increasing global temperatures have, as expected, vaporized more water that has remained in the atmosphere. It has increased the total global water vapor content. Instead of reducing this increased humidity through precipitation, the increasing water content is found primarily in the tropical upper atmosphere. This, in turn, results in a stronger greenhouse warming from the increased water vapor present, with resulting increased temperature, which evaporates more water, etc. Thus, a **positive feedback loop** is apparently present.

Mechanisms for cleansing the atmosphere of greenhouse gases; sources and sinks

Greenhouse gas molecules are not very sensitive to the Earth's oxidizing atmosphere. For example, water and carbon dioxide are already fully oxidized and the OH radical and other oxidizing agents do not affect their atmospheric concentration. The carbon-hydrogen bond in methane as well as the carbon-fluorine and carbon-chlorine bonds in CFCs are all resistant to attack by the OH radical. Therefore the lifetimes of many greenhouse gas molecules in the troposphere are relatively long, when compared with other more easily oxidized organic air pollutants.

The atmospheric concentration of any greenhouse gas at any given time depends upon two factors: the rate of its introduction into the atmosphere (**source**), and the rate of its destruction or removal (**sink**) from the atmosphere. When the source introduction rate is faster than the sink removal rate, the net greenhouse gas concentration increases with time. It would appear that the source and sinks for methane (more recent data not shown) are nearly equal, since the methane curve in Fig. 6-13 appears to be leveling off. In the case of CFCs, they are decreasing with time because their commercial production has ceased. However, the competing source and sink processes have been out of balance for about a century for carbon dioxide and nitrous oxide. An analogy would be a household sink that drains poorly and overflows if the flow rate of water into the sink is faster than the rate at which the sink drains and spills on the floor. This is currently the case with CO_2 and N_2O.

The absolute number of molecules of a particular greenhouse gas is only one of the important factors to consider as the cause of global warming. Another important consideration is the effectiveness of a specific greenhouse gas molecule in absorbing infrared photons. Methane and CFCs are far more effective than carbon dioxide as greenhouse gases. That is, per molecule, methane has a higher probability of absorbing an infrared photon than a carbon dioxide molecule.

Feedback and Clouds

Clouds help cool the planet, because at any given time, over half of the surface of the Earth is covered with clouds, most of which reflect sunlight back into space. Low clouds, such as cumulus, are more effective at reflecting sunlight than others, such as high cirrus clouds (Fig. 6-14). In any global warming scenario, there will be more moisture released to the atmosphere because higher temperatures will break more hydrogen bonds between liquid water molecules, leading to more water vapor being generated.

Also, more heat will be released to the atmosphere when this excess water vapor condenses. The quantity and type of clouds that result from this increase is one of the most critical aspects of the construction of global warming models (see below). If clouds are dropped out of the models, there is generally good agreement among all the models. When clouds are included in the models, a significant variation in the results among the various models is observed. However, the physics and chemistry of cloud formation is complex and incompletely understood. Claims have been made that cosmic rays bombarding the Earth's atmosphere are important causes of cloud formation and may be responsible for climate changes that correlate well with changing cycles of cosmic radiation from the Sun.

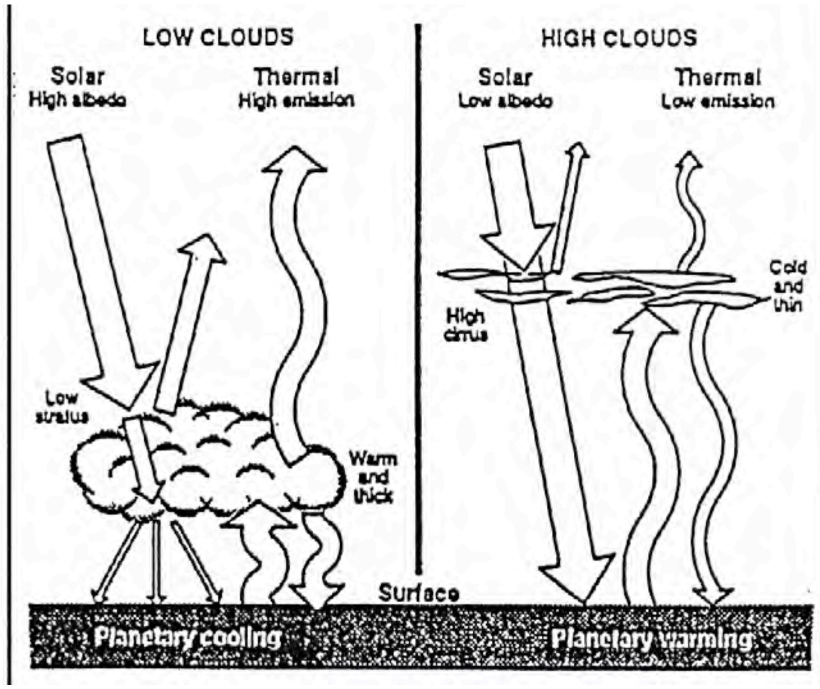


Fig. 6-14 Two types of clouds causing either cooling (stratus) or warming (cirrus) because of their reflectance and structure.

Global temperature trends

It would be very easy to conclude that the upward trend in temperature in Fig. 6-15a, i.e. the apparent global warming trend, is due to the increasing concentration of greenhouse gases. However, one problem with this assumption is that global temperatures and methane and carbon dioxide concentration vs. time have different curve shapes for the past century. To be valid, any theory or computer model of global warming must explain the critical fact that, despite the continuously increasing concentrations of carbon dioxide and methane, the average world temperature during the 1940 to 1970 period was approximately constant, possibly even declining. Any theories of global warming must be able to explain this decrease in temperature.

However, since 1970, there is no letup in the increasing global temperature trend. We examine the trend line in Fig. 6-15(a) rather than year-to-year temperature differences because there are cooling influences that have nothing to do with greenhouse gas concentrations. There is natural climate variability, as seen from the scatter in the raw data [gray circles in Fig. 6-15(a)]. Sulfate aerosols that peaked in the 1970s have decreased in North America, but increased recently in Asia. Solar intensity varies in faily regular cycles and there are temperature changes in the eastern tropical Pacific ocean called El Niño and La Niña events that have a major impact on the climates of North and South America. Despite predicted global cooling from historic climate trends, global temperatures toward the end of the first decade of the 21st century were unexpectedly high and record breaking, implying that greenhouse gases are responsible. Although cooling is anticipated from the above described events, this cooling is apparently overridden by temperature increases due to greenhouse gas "forcing."

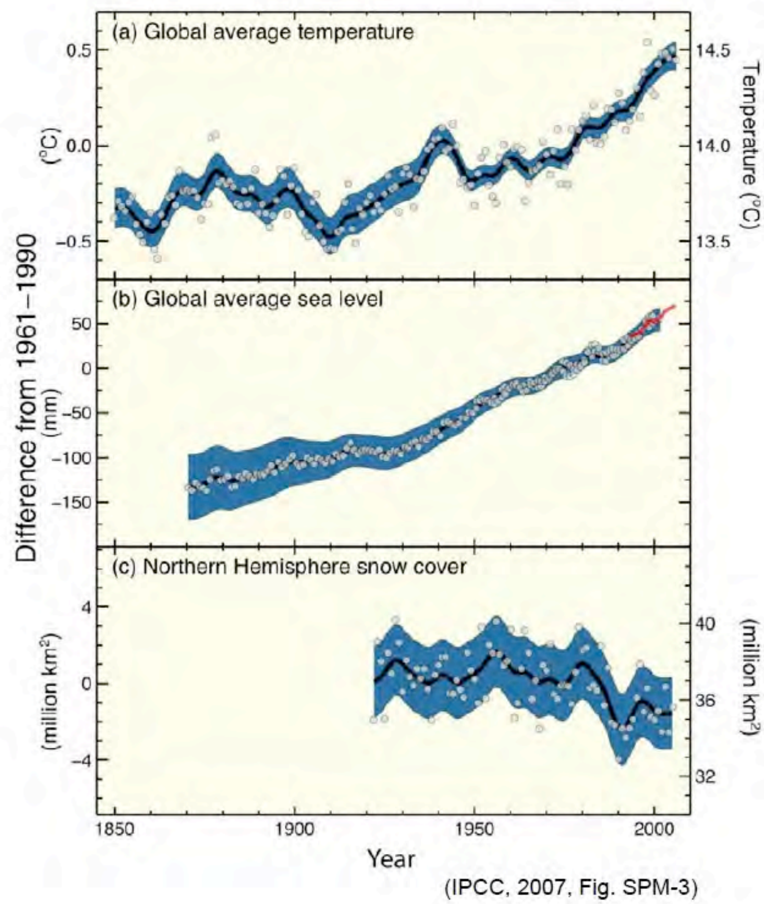


Fig. 6-15 Trends in global temperature, sea level. IPCC 07

Better methods of measuring the temperature of the tropical upper troposphere have shown warming in this region in recent years. Scientists propose that this is the result of larger amounts of water vapor in this region.

Glacier melt and rising sea levels

Glaciers and mountain ice-caps provide fresh water in many mountain regions and stream valleys around the world. If all of the world's glaciers and ice-caps were to melt, the water released to the seas would contribute a total of a little less than one meter in sea-level rise. Since the 1990s, many of the Earth's glaciers and mountain ice-caps have retreated. Many of the glaciers in Glacier National Park have disappeared and more are expected to meet that fate in the future. According to scientists studying these effects, the reasons for this rapid disappearance are from two causes, rising world temperatures (Fig. 6-15a) and natural climate variability, such as the rhythmic multidecadal rise and fall of the temperature of the Atlantic Ocean. The estimated contribution of melting of glaciers and ice-caps to global sea-level rise has increased from 0.8 mm per year in the 1990s to 1.2 mm per year in 2009 (Fig. 6-15b). Current glaciers and ice caps are not in balance with the present climate conditions and their melting is expected to contribute to future sea level increase. However, the thermal expansion of the oceans from atmospheric warming is expected to dominate in its contribution to sea level rise.

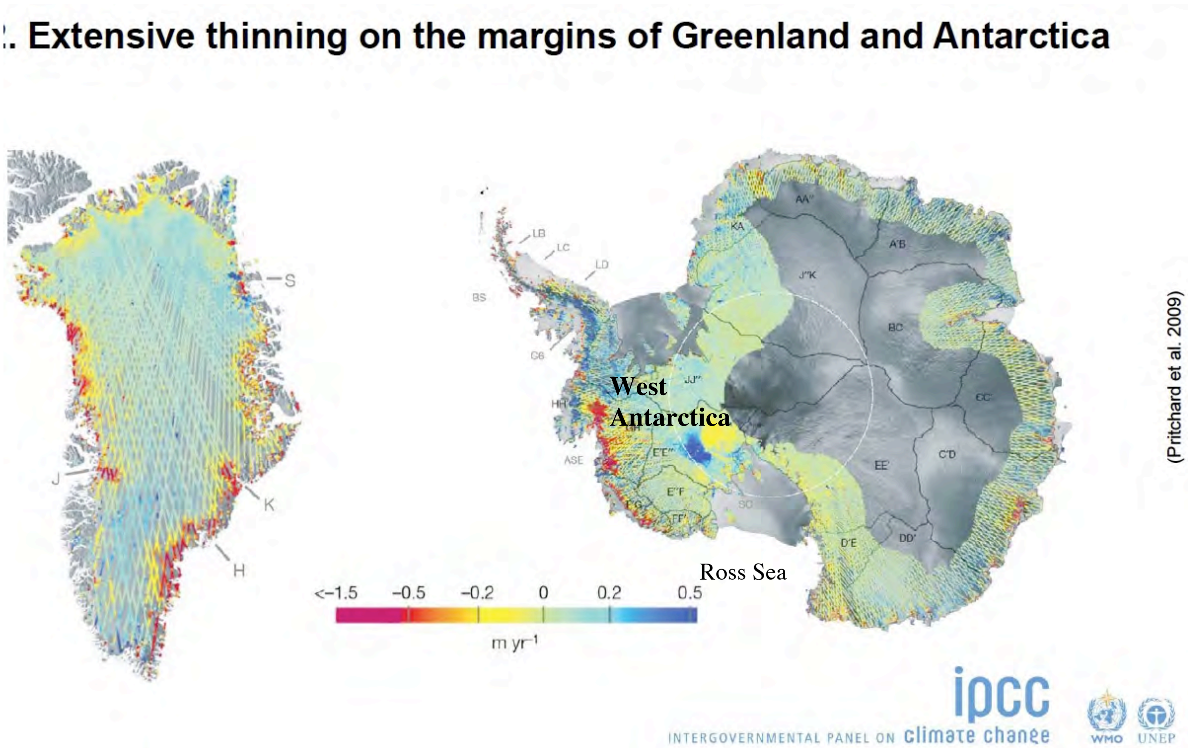


Fig. 6-16 Extent of recent ice sheet thickening (green to black) or thinning (yellow to red) in Greenland (left) and the Antarctic (right).

Climate changes in Greenland, Antarctica, and the Arctic

Snow in polar regions goes through an aging cycle. For example, the small snow flakes alter over time, forming larger and darker crystals, reflecting less light and more prone to melting from absorbed solar radiation. Air pollution brings industrial soot which layers on top of ice sheets and may further increase the amount of solar radiation absorbed, providing heat that can melt ice. As the height of an ice mass lowers, the temperature may be higher. The massive ice sheets on Greenland have shown signs of accelerated melting and a disturbing increased flow toward the sea during the late 1990s. If the entire approximately 3 million cubic kilometers of Greenland ice were to melt, it would cause a global sea level rise of approximately 7 meters (about 24 feet). One of the concerns is the relatively recent extensive melting on the surface of this sheet causing extensive pools of meltwater (Fig. 6-16). Drain holes have been discovered that carry away millions of gallons of this meltwater. It is difficult to explore the fate of this water, but the worry is that it can lubricate the interface between the massive ice sheet and the ground underneath the ice sheet and signigicantly increase the rate of its flow toward the sea. In August 2006, the flow suddenly slowed down and stabilized. Many breathed a sigh of relief, but the exact mechanism of both the relatively sudden acceleration and deceleration is not known. Since 2006, there has been erratic movement of these ice sheets, with no clear ice sheet movement trend. However, satellites that detect the mass of the ice sheet show declines in ice sheet mass over time.

By far the largest ice mass in the world is found in the Antarctic (Fig. 6-16). Much of its ice is bound to the land and cannot move toward the sea except as meltwater. The major glaciers in this region are the eastern ice sheets, which extend into the Ross sea. The West Antarctic ice sheet and shelf extends into the ocean and is thought to be much less stable because it can be melted from below by warming ocean water and thus collapse into the ocean and melt (Fig.6-17). For more detail, click here.

(Link) The structure of Antarctic ice sheet is critical (Fig. 6-17). The continued flow of ice toward the sea forms large ice sheets or tongues that are grounded on till deltas. These sheets are in contact with the ocean. When the ocean warms, it is suggested that this weakens the ice shelf sufficiently that it breaks off large ice blocks that float away, releasing the back pressure preventing the movement of large ice streams. The ice shelves act like buttresses preventing flow of ice toward the sea and when the ice shelf breaks up there is nothing holding back this flow toward the sea of the ice stream Fig. 6-14a. The West Antarctic ice sheet is especially vulnerable to ice shelf removal because much of that ice sheet rests on bedrock several hundred meters below sea level. Loss of the entire West Antarctic ice sheet would raise sea level 6 to 7 meters (20 to 25 feet) and open up a path to the ocean of the much larger East Antarctic ice sheet. This type of event might also occur in Greenland. None of these events are included in IPCC climate models.

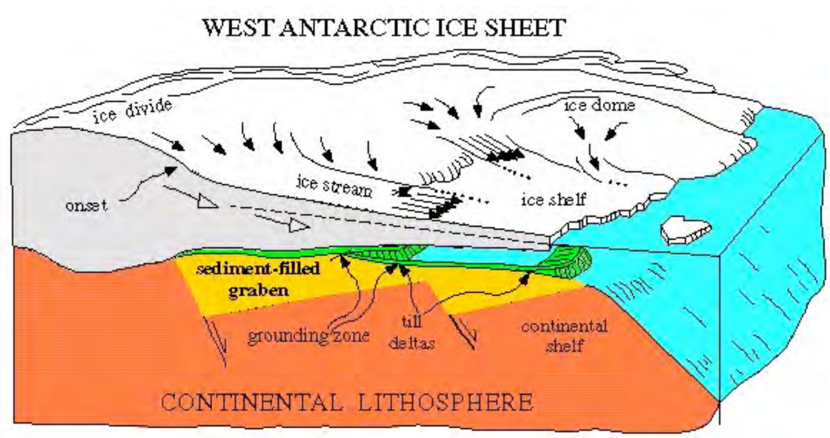


Fig. 6-17 Details of Antarctic ice flow toward the sea.

In recent decades, the most definitive climate changes have taken place in the Arctic, where the rise in near-surface air temperatures has been almost twice as large as the global average. This feature is known as the “Arctic amplification.” All climate models predict these very high temperatures indicating that they are the result of a loss of snow and sea ice, allowing more sunlight to be absorbed by the larger

Southern Ocean surface in a feedback process that amplies the warming. In the summer of 2009, two cargo ships navigated the ice-free Northwest and Northeast Passages through the Arctic Ocean for the first time. These higher temperatures have caused unprecedented ice melting and changes in Arctic vegetation and sea-life.

The above process is the result of what is designated as a **positive feedback cycle**. Snow and sea ice has a high **albedo** (a large fraction of the incoming sunlight is reflected). When parts of this ice region melt to produce dark water that absorbs rather than reflects light, the water temperature and therefore the air temperature increases. But this increased air temperature causes more ice to melt, which causes more water to be exposed, which causes a further increase in air temperature, etc. The result is that, because of this positive feedback loop, it is predicted by some that during the summer the Arctic will be ice-free and contain less snow on land by 2050. Snow cover has decreased in addition to sea ice.

Causes of sea level rise

For the past 7000 years, the sea level has been stable. This has allowed civilizations to be established near the sea. However, much earlier, during the depths of the ice ages, sea level was as much as 110 meters lower than today. The missing water was on the continents in the form of massive ice sheets that covered much of Canada and western Europe. As the ice sheets melted, the rise in sea level was 4 to 5 meters per century.

Sea levels rise for at least four reasons, of most concern being the movement of large ice masses from land to sea. The melting of ice caps or mountain glaciers has already been mentioned. On the other hand, rivers whose source is not melting ice and that run into the sea, even at flood stage, should not cause a net increase in sea level, since this cylcing process of evaporation, precipitation, and drainage back to the sea is part of the solar driven hydrologic cycle (Chapter 4 link).

When pure ice melts in pure water, there is no change in the water level in a glass. However, if this experiment is run in salt water there is a slight rise in the diluted salt water solution level. This is because there is a difference in the density of salt and fresh water. The circulating “ocean conveyor belt” is driven by this density difference (link). Thus, when ice contained in icebergs melts, the density of the diluted seawater is decreased and it expands, increasing the volume and raising sea level. If the hydrologic cyle is out of balance with respect to the rate of snow and ice formation in polar or glacial regions vs melting of this ice in the ocean, this will cause a sea level change. If there is more ice formed than melted, the sea level will decrease. If there is less ice formed than melted, there will be an increase in sea level.

Finally, and much more significant, as we have seen in Chapter 4 (link),when water is warmed above 4ºC, it expands. Therefore, if the temperature of the ocean is increased, this, too, will cause a rise in sea level. The sea has many different temperature levels, so the amount of expansion depends on the depth and extent of the warming.

One prominent climate scientist, James Hansen, claims that, based on historical climate data, once the massive ice sheets of Greenland and Antarctica start to melt, there will not be a stable sea level for the forseeable future. Transitions, he predicts, will not be smooth either. Scientists are just learning about the physics of large ice sheets and do not know much about how they will melt, what the thresholds are, or whether melting will proceed at rates seen in the past or faster (because the forcing is now different). Hansen's predicition is that sea level rise could be rapid, and increased sea level plus stronger storms would lead to more flooding of coastal cities in most of the readers' lifetimes. If so, coastal cities could become impractical to maintain. Sea level changes to heights at least several meters greater than today's level occurred in interglacial periods that were at most 1 to 2 degrees C warmer than today.

Ocean as a sink for CO_2 and heat

Ch6/Oceans/p.1

The ocean has an immense capacity to hold and to distribute heat energy. The Atlantic Ocean Gulf Stream is the most familiar example of the latter. Without this warming ocean flow, the mean temperature of Europe would be lowered by more than 5°C. Oceans are dynamic carriers of heat energy from the tropics to the poles. The Gulf Stream is only one small part of what has been called the "great ocean thermohaline conveyor belt" illustrated in Fig. 6-18a and 6-18b. This postulated global circulation of the heat energy and salt water takes warm equatorial ocean *surface* water and moves it through the Pacific between Australia and Indonesia through the Indian Ocean, around Southern Africa and up the Atlantic to Greenland. During the journey north through the Atlantic Ocean, large amounts of water vaporize. Much of this water vapor is transported from the Atlantic Ocean to the Pacific Ocean. This vaporization causes an increase in salt concentration and water density as the ocean water approaches the North Atlantic ocean.

Fig. 6-18a The ocean conveyor belt. Driving this belt is the cold, highly saline North Atlantic ocean water that sinks because of its higher density than the water below it.

Ch6/Oceans/p.4

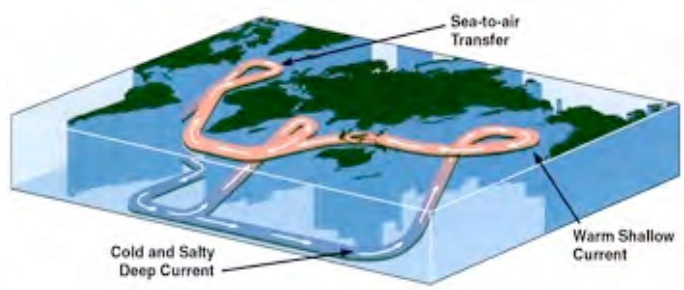


Fig. 6-18b A three dimensional representation of the conveyor belt.

In the North Atlantic, Arctic air cools the water[Freeze – saltier water]. This cooling, combined with its high salinity (salt concentration), increases the salt water density, causing the water to sink to depths greater than a thousand meters. Ocean surface winds also play a role in this process. This descending escalator of cold water is then transported in a wide column (wider than shown in Fig. 6-18) of *intermediate and deep* waters slowly southward along the Atlantic toward the Antarctic, where it joins a rapidly moving deep current that encircles the Antarctic continent in the Southern Ocean. Here it is efficiently mixed with other deep waters. Part of this cold, deep flow is diverted toward the Indian Ocean, where it upwells (brings water from the deep ocean to the surface) and picks up heat from the tropical ocean air and water, remains on the surface, and starts the cycle over again. Another part of the deep current moves northward east of Australia to the northern Pacific where it surfaces and picks up heat as it flows southward on the surface toward the equator. The rest of the deep Antarctic current upwells in the Antarctic.

The above conveyor belt hypothesis has been reexamined in recent years and many critics believe it is too simple. In particular, it was based on a reltiavely limited set of observations. Observations in larger areas of the ocean in greater detail show much more complex circulation. Basically, there are two layers of the ocean. The surface layer, in direct contact with the atmosphere, is well mixed. The other lower layer is a vast amount of very cold water that sank at polar lattitudes and remains isolated from the surface for hundreds to thousands of years.

Studies of ice cores in Greenland have achieved a higher time resolution than is achievable in the Antarctic ice core studies. Because *annual* layers of ice can be detected up to 14,500 years ago in these ice cores, a surprising discovery was the observation of a series of temperature oscillations of *as much as 6 ºC in time spans of less than a decade*. These very large temperature excursions have been attributed to cessations and restarts of the thermohaline ocean conveyor belt. One hypothesis proposed is that fresh water from heating episodes suddenly stalls the conveyor for a short period followed by a startup again, with the abrupt changes in Greenland temperature.

More extensive experimental facts are needed to understand the vast ocean circulation system. What is becoming obvious is that increasing CO_2 and temperatures both will involve interactions with the world's oceans. The ocean has the capability of being a vast **sink** (repository) for both increasing atmospheric heat and CO_2. Recent research has shown that within the last several decades, the ocearns' capacity for absorbing heat and CO_2 is probably decreasing and perhaps even showing signs of approaching limits for each of these. We need to know more about the ocean to be able to answer the questions, what are the limits? and how close are we to those limits?

Ocean Acidification Ch6/Oceans/p.2

When carbon dioxide dissolves in water, the following reactions (6-2) and (6-3) take place:

$$CO_2\,(gas) + H_2O \leftrightarrows H_2CO_3 \qquad (6\text{-}2)$$

$$H_2CO_3 + H_2O \leftrightarrows HCO_3^- + H_3O^+ \qquad (6\text{-}3)$$

The double arrow ($\leftrightarrows$) indicates that the reaction proceeds toward a stable equilibrium where reaction rates are equal in both the forward and reverse directions. That is, despite the forward and backward reactions, the system of reactions comes to an equilibrium in which all concentrations of the reactants and products in the system remain constant even though reactions are still taking place. The existence of the reverse reaction in equation (6-3) following the ionization of the weak **carbonic acid (**H_2CO_3) means that this acid is relatively weak. This means that whenever a hydronium ion is formed from the forward reaction (6-3), it is highly susceptible of undergoing the reverse reaction in equation (6-3). However, there is still enough extra hydronium ion (H_3O^+) present to change the pH of a solution of pure air-free water from 7 to about 5.5 for air-saturated water, merely from the small amount of CO_2 originating from the dissolved air.

As the atmospheric concentration of CO_2 has increased with time, more of this CO_2 enters into all waters exposed to the atmosphere. This dissolved CO_2 yields a higher H_2CO_3 concentration, which, in turn, ionizes to give a higher steady state H_3O^+ concentration. Thus, the pH of all bodies of water exposed to the atmosphere should have had their pH *lowered* because of the higher hydronium concentration.

Measurements of seawater have demonstrated significant changes in pH during the last decade. For example, the pH of the top 550 meters of the Pacific Ocean near Hawaii changed by 0.026 pH units. Since the beginning of the industrial period the pH, researchers estimate that the pH of the global oceans has changed by 0.1 pH unit. This may appear to be a tiny change, but because pH is a logarithmic unit, this corresponds to a 30% increase in ocean hydronium ion concentration, a quite significant change.

What are the implications of this change in ocean acidity for marine life? This is really hard to predict since the oceans harbor delicately balanced ecosystems, whose life processes are all sensitive to pH. For example, many marine species depend on the formation of solid $CaCO_3$ shells (for more info click here).

——————————advanced material——————————

The formation of these shells depends on the concentrations of both calcium ions (Ca^{2+}) and carbonate ions (CO_3^{2-}) in the ocean water. The formation and dissolving of shells in seawater is represented by the equation (6-4). Note that this is a reversible reaction.

$$Ca^{2+}(aqueous) + CO_3^{2-}(aqueous) \leftrightarrows CaCO_3\ (solid) \quad (6\text{-}4)$$

However, the above reaction is dependent on the aqueous carbonate ion concentration. This ion concentration, in turn, is dependent on the hydronium ion concentration, as indicated in reactions (6-5) and (6-6). The carbonate ion concentration can be lowered in a sample of seawater by simply adding a small amount of acid. Reaction (6-5) consumes both the added hydronium ion and carbonate ions present in the seawater producing the bicarbonate ion product. Reaction (6-6) takes the product of reaction (6-5), the bicarbonate ion, and reacts it with any remaining hydronium ion. The formation of carbonic acid, H_2CO_3, now involves this carbonic acid in reaction (6-7) in the formation of dissolved carbon dioxide, which can now escape into the atmosphere as gaseous CO_2.

$$CO_3^{2-} + H_3O^+ \leftrightarrows H_2O + HCO_3^- \quad (6\text{-}5)$$

$$HCO_3^- + H_3O^+ \leftrightarrows H_2CO_3 + H_2O \quad (6\text{-}6)$$

$$H_2CO_3 \leftrightarrows CO_2\ (gas) + H_2O \quad (6\text{-}7)$$

Increasing the hydronium ion concentration because of increased carbon dioxide in the atmosphere decreases the CO_3^{2-} concentration because of the forward reaction in equation (6-5) and therefore lowers the carbonate ion concentration and produces the product bicarbonate ion (HCO_3^-). This lowered carbonate ion concentration may threaten shell formation or cause thinner, more fragile shells. Experiments with variable amounts of CO_2 in their water caused mass mortality of oyster larvae forming their first shells above a certain CO_2 concentration. When the hydronium ion concentration gets high enough, the $CaCO_3$ shell in shell-containing marine organisms begins to dissolve according to the reaction (6-8).

$$CaCO_3 \text{ (solid)} + H_3O^+ \leftrightarrows Ca^{2+}\text{(aqueous)} + H_2O + HCO_3^- \qquad (6\text{-}8)$$

Because of the cycling of ocean water, one might think that the ocean would "flush" the excess CO_2 from the ocean surface. However, this is a very slow process – on the order of 1,000 years. Thus, ocean acidification is rapidly becoming one of the indicators of potential irreversible global climate change. The ultimate fate of the excess carbon dioxide is to dissolve solid $CaCO_3$ present in sediments on the ocean floor, but the process is very slow

————————————end of advanced material————————————

Negative effects of pH change on sealife

Over geological history, relatively sudden changes in ocean pH have had a drastic effect on ocean ecosystems. 250 million years ago, carbon dioxide atmospheric concentrations probably doubled because of a massive volcanic eruption. More than 90% of all marine species disappeared. A completely different ocean, with relatively few species, persisted for four to five million years.

In a 2010 review (Science, vol.328, 18 June 2010, pp1523-1528), the authors maintained "Recent studies indicate that rapidly rising greenhouse gas concentrations are driving ocean systems toward conditions not seen for millions of years, with an associated risk of fundamental and *irreversible* [emphasis added] ecological transformations. The impacts of anthropogenic climate change so far include decreased ocean productivity, altered food web dynamics, reduced abundance of habitat-forming species, shifting species distributions, and a greater incidence of disease. Although there is considerable uncertainty about the spatial and temporal details, climate change is clearly and fundamentally altering ocean ecosystems."

For example, a number of types of marine life must expend excessive amounts of energy to balance the changing pH of the ocean against their own internal pH. This extra effort has affected their ability to reproduce and grow. Many species are unlikely to adapt to ocean acidification, because it is happening so fast. There are some indications that corals are "migrating" toward the poles. Not all marine species may be that adaptable.

Thus far we have discussed the effects of greenhouse gases on climate. What are the other possible causes of climate change?

Extreme temperature and weather events

There have been, since the 1970s, increases in high temperature extremes and decreases in low temperature extremes around the world. However, there are exceptions to this generalization due to changes in land use. The influence of global warming is clearer in extreme weather events. Increased temperatures cause more evaporation of water into the atmosphere which carries with it latent heat energy stored in water vapor during the evaporation process. This means that the water is carrying excess thermal energy, which is released as heat when that water vapor is transformed back into liquid or solid precipitation. When more water vapor enters the atmosphere at higher temperatures, there is more latent heat energy to power storms and other weather events. When very large amounts of energy are available, the weather event, such as in a hurricane or a tornado, it is classified as an extreme event. The percentage of events classified as extreme is graphed in Fig. 6-16. It would appear that since 1970 these events have been increasing, as indicated by the 5-year moving average. In addition, since 1970, there have been increases in droughts. Data on tropical hurricanes and typhoons is not as clear cut, but would also appear to indicate an upward trend since the mid-1970s. This trend is strongly correlated with the rise in tropical sea surface temperatures. Increases in severe thunderstorms and wildfires have also been noted.

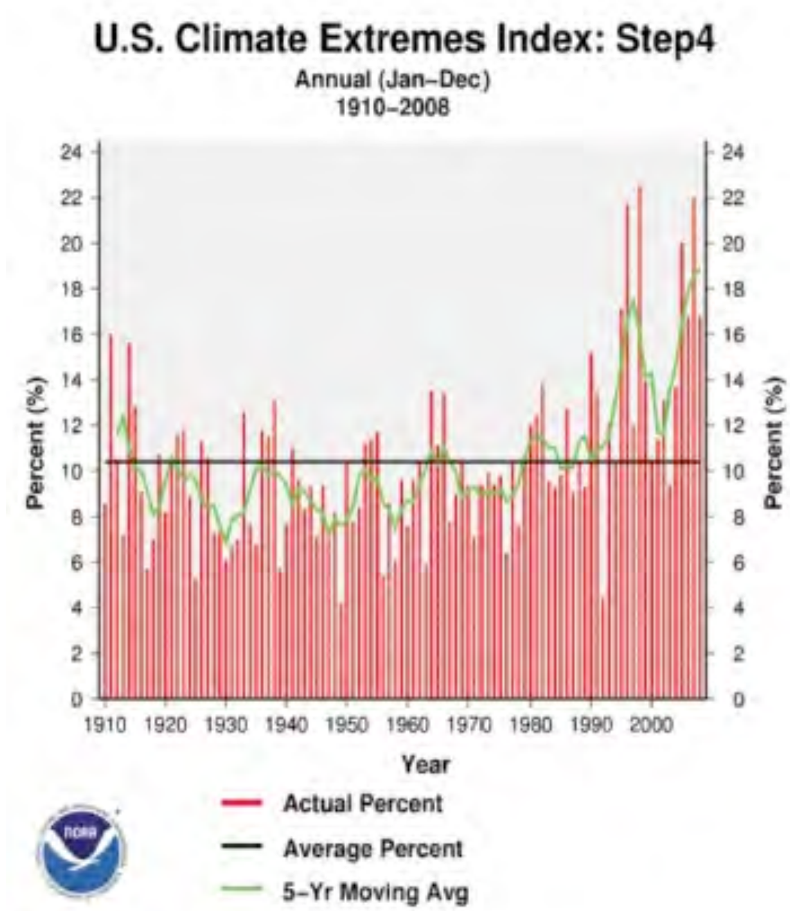


Fig. 6-16 Percentages of climate extremes including high and low temperatures, floods, tornadoes, hurricanes, violent storms,

Predicting the Future Global Climate

The IPCC (Intergovenmental Panel on Climate Change)

When it became obvious in the 1970s and 1980s that global warming and climate change were among the most important international environmental problems, the

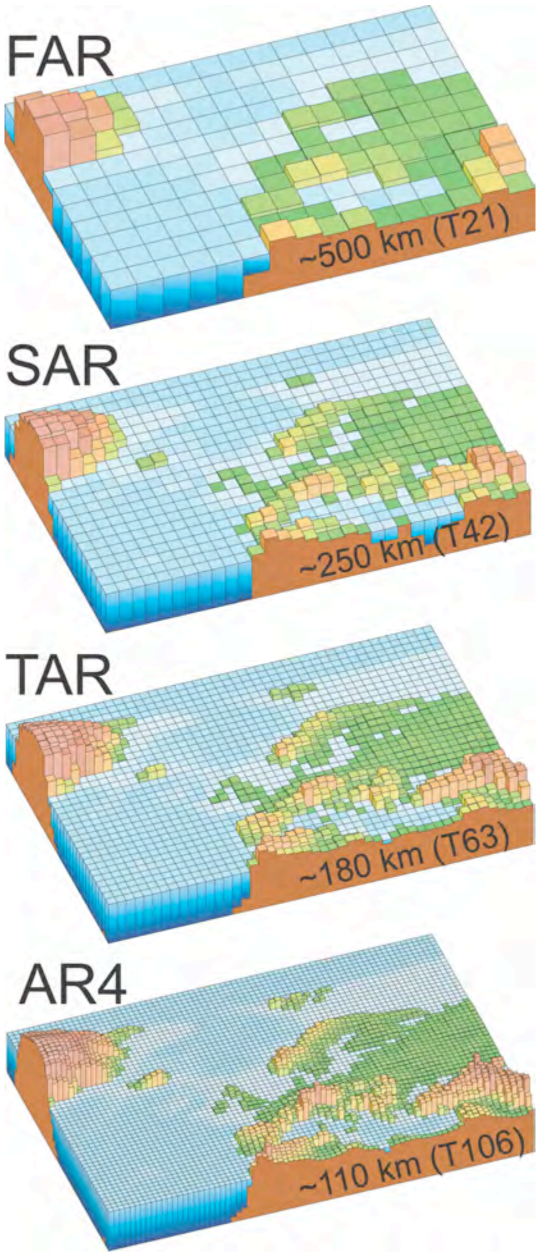


Fig. 6-19 Different computer models from four successive IPCC (Intergovernmental Panel on Climate Change) Assessment Reports [First(FAR), Second(SAR), Third(TAR), Fourth(AR4)]. Each model divides up the world into smaller "chunks" and becomes more refined. Europe and the North Sea are shown above. Current models are even more finely divided and therefore more accurate representations.

United Nations Envionment Programme (UNEP) and the World Meterological Organization in 1988 established the Intergovernmental Panel on Climate Change (IPCC). This organization has both a scientific and a governmental component. Its mission is to "….to assess on a comprehensive, objective, open and transparent basis the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation." The IPCC is composed of panels of thousands of leading experts from around the world working in the various fields of climate research. Thus the main focus of the IPCC is to collect relevant data on past and present climate change indicators, to predict future trends in climate change, to assess their impact, and suggest ways of dealing with the potential or existing problems of climate change.

Within IPCC, there are three working groups of unpaid volunteers: (1) Group I: The Physical Basis of Climate Change assesses the scientific aspects of the climate system and climate change (considering only peer reviewed papers); (2) Group II: Climate Change Impacts, Adaptation and Vulnerability assesses the vulnerability of socio-economic and natural systems to climate change, negative and positive consequences of climate change and options for adapting; (3) Group III: Mitigation of Climate Change assesses options for limiting greenhouse gas emissions and other options for mitigating climate change. Major IPCC Assessment Reports have been released in 1990 (FAR), 1995 (SAR), 2001 (TAR), 2007 (AR4), and another will be released in 2013 (AR5). The 2007 Nobel Peace Prize was awarded to the several thousand IPCC volunteer scientists and to former US Vice President Al Gore for "for their efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change."

[In the interest of full discosure, the lead author of this book (CT) indicates here that his daughter, Susan Trumbore, was a scientist author on a special report on land use, land use change and forestry for Working Group I in the 2007 AR4 Report. Thus, the author is not without a certain amount of bias toward IPCC reports and recommendations, which form much of the basis for the rest of this chapter. Susan is also a consultant for this Contemporary Chemistry project chapter and uses some of the animations from this project in her teaching.]

Climate Computer Models

Modeling current and past temperatures

Computers are used to predict weather and to make predictions of climate change. Models are used in both of these endeavors, but are quite different in their aims and programs. Both are sensitive to initial conditions fed into the computer programs. Weather evolution is chaotic and short range. Climate is a statistical summary of the average, range and variability of weather (temperature, precipitation, wind) over many years. Weather models are beginning to be used to detect trends in extreme events, for example temperatures in a particular month of the year.

Because we have only one earth, we cannot run a controlled experiment to see what climate would have been like without the current increases in greenhouse gases. We therefore have to make a model Earth to test our understanding of the complex climate system and to predict possible future climate change. By taking the pertinent experimental data and the applicable scientific and computational tools, scientists generate computer models that, they hope, can accurately predict future global temperature and general weather trends as well as justifying past trends with these same models. These are called **General Circulation Models** and the scientists who make these educated guesses are called “global modelers.”These forecasts are featured in and are the basis for many of the conclusions and predictions of the various IPCC Asessment Reports.

There are many difficulties in forecasting weather, either for the short range (days) or the long range (months to decades). What is being asked of global modelers is to make twenty- to fifty-year forecasts when the success of a 90-day forecast is no better than about fifty percent. Problems arise with the 90-day forecasts because of ocean disturbances, such as the infamous El Niño and La Niña events [link to definitions] in the equatorial Pacific ocean, that can strongly affect weather systems in other parts of the world. Other, even more serious problems with weather forecasting have recently been recognized. These problems are related to a discipline called “chaos theory,” proposed by a theoretical meteorologist, Edward Lorenz. Lorenz found that his weather forecasts were supersensitive to very small changes in the absolute values of his computer input variables. This means that exceedingly small changes in the values he used as computer inputs to predict weather led to completely different forecasts. This is also known as the “butterfly effect” (a butterfly flitting its wings in Atlanta could affect the outcome of a major storm in the Pacific Ocean).

The many parameters that are incorporated into these complex General Circulation Models include: the hydrologic cycle, ocean processes and biogeochemistry, sunlight flux for different regions and solar cycles; water-air interfaces, water-ice interfaces, ice formation and melting, light absorption and reflectance of clouds; sources, sinks, and absorption efficiencies of greenhouse gases for various electromagnetic radiations; particulates and aerosols; albedo (light reflection characteristics) of the various parts of the Earth; wind patterns; probability of volcanoes; heat sources and sinks, and land uses, biosphere interaction with air, heat transfer to and from the atmosphere, oceans, and land masses, which are divided into layers in these models to give a large number of cells covering the globe (Fig.6-19). Basic equations of motion for gases are built into the model to account for movement of gases between cells. Other equations determine the amounts of the different types of ultraviolet, visible and infrared radiation that are absorbed in the different cells. Outputs into the atmosphere of greenhouse gases are estimated from industrial and agricultural data. The exchange of energy between the atmosphere and the land, ocean, snow, ice, clouds and vegetation is estimated. Supercomputers then calculate the effects of increased greenhouse gas concentrations on global temperatures, wind patterns, sunlight, relative humidity, and precipitation for each cell on the globe. As much as a month of computation may be required for a single result, for example, the increase in average global temperature resulting from a doubling of the carbon dioxide concentration by the year 2100. As computing power increases, models are able to be made more realistic.

There are many different climate models being studied in research groups from many different countries. Most modelers are now using many common starting points (initial starting dates) and initial inputs (e.g., sea and land temperatures) in their models. This allows comparison of models to observe sensitivity to different input parameters in the different models. For example, the treatment of cloud formation and types of clouds formed is a difficult problem for all models. IPCC Assessment Reports are focussed on the areas of agreement and disagreement of these models. Working Groups II and III are dependent upon these model outputs for their own social and economic predictions as well as recommendations for mitigation strategies. Thus it is quite important to make sure that the scientific foundations of these models are as rigorous as possible. This is why, to be treated as valid, the model must be able to fit all or most of the known data up to the present time, including regional trends in temperatures, ocean currents, sea level rise, etc.

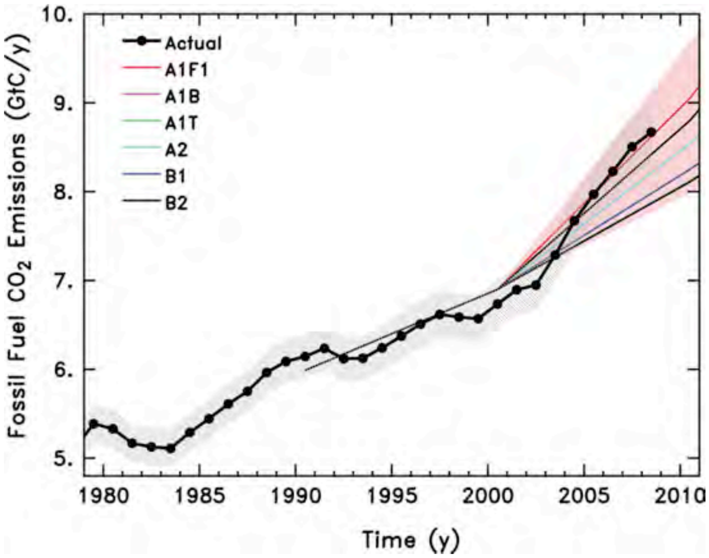


Fig. 6-20 Fossil fuel carbon dioxide emissions over the last thirty years. On the right side, the pink band shows the various projections used in the IPCC TAR (2001) computer models.

One input into these models is how much greenhouse gas will be present at future dates. For example, in earlier IPCC models, a variety of projections for CO_2 emission from fossil fuels were postulated (Fig. 6-20 - Lines within the pink band starting in 2001). The black dots in Fig. 6-20 plot the actual fossil fuel CO_2 amount measured, demonstrating that we have nearly exceeded the "worst case" scenario (A1F1).

One thing must be stated about computer models: they are only as good as the assumptions made in constructing the model and values of the parameters that are fed into the model. One of the most uncertain of these is the amount of excess anthropogenic CO_2 that will be emitted into the atmosphere in the future. They are also highly dependent on the data that are fed into the starting point in the computations. Thus far computer models have underestimated the sea level rise and the rate of melting of ice sheets and glaciers, so there is improvement needed in these models. One modeler, James Hansen, indicates that the lack of proper models for ice sheet melting means that models cannot be relied on for predicting catostrophic events that may lie ahead. He suggests that we should rely more on historic climate change data for the ice ages as better predictors of

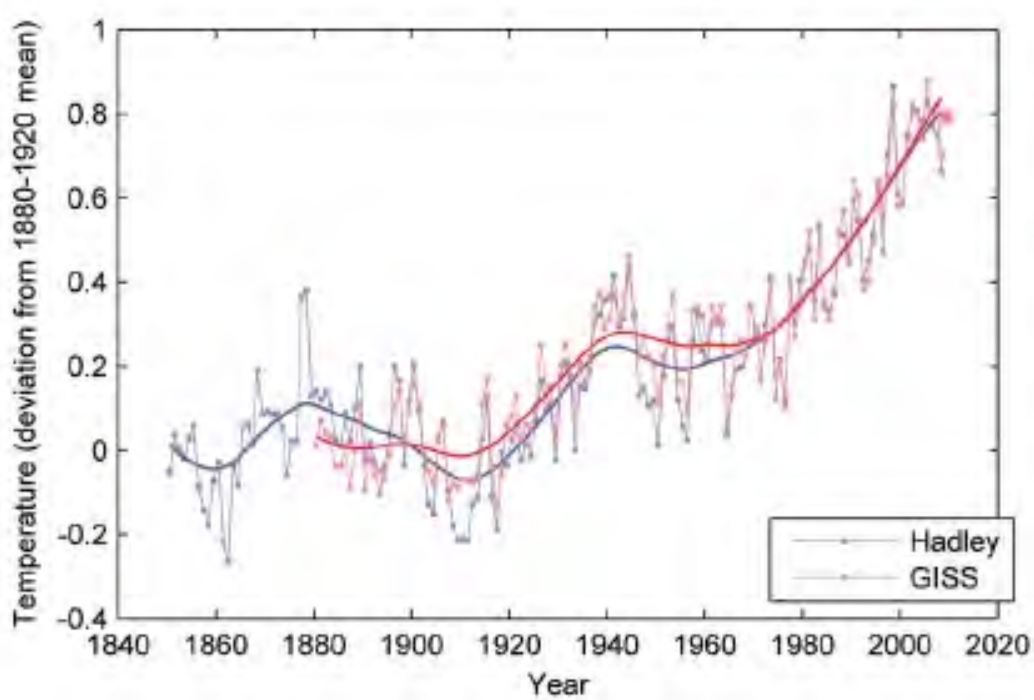


Fig. 6-21 Average global temperatures from two different major research groups. Solid lines are mean temperatures that average out what appear to be "wild" fluctuations so that trends are more easily detected.

indicators of climate sensitivity and potential trends in the future. This despite the fact that he and his group are working on one of the models whose results are included in the IPCC recommendations.

Once a computer model is able to "predict" past long-term climate trends, it is ready to attempt predictions of the future climate and temperatures for different parts of the world, given different scenarios of buildup of the different greenhouse gases with time, future formation of aerosols, and normal volcanic activity. Enough reliable models have been grinding out predictions long enough now to observe their ability to predict into the future. Measured global temperatures have been in agreement with model predictions based on increased greenhouse gases concentrations. Over the past 27 years, average temperatures have increased at a rate of 0.19ºC per decade. What has been illuminating has been the *under*predictions of models of such things as carbon dioxide concentrations and Arctic temperatures.. Climate models are continuously being compared with obsevations to further improve our admittedly imperfect understanding of all of the complexities of climate change. So far, observations show responses that lead to concern, like the Arctic sea ice. These show us where more understanding is needed, and where possible thresholds need to be identified and included in the models.

Uncertainties in climate models arise from uncertainties in each of the following: initial conditions (values for every variable in the model, including uncertainties for each of these values), future greenhouse gas concentrations, intensity and frequency of volcanic activity, deviations from historical solar cycles, and uncertainties because some processes are not fully understood or are impossible to resolve due to the inability to represent these in a computer program. The final test of any model is whether it not only is able to predict future trends, but also fit data from the past with a minimum of parameter adjustment without logical reasons. However, the biggest uncertainty is what people will do in the future. That is, how much CO_2 will they emit, what forests will they cut down, etc.

Fig.6-22 shows calculation summaries with and without greenhouse gas "forcing" (climate perturbations) included. The blue trend lines in various locations throughout the world are based on having no greenhouse gas contributions. These

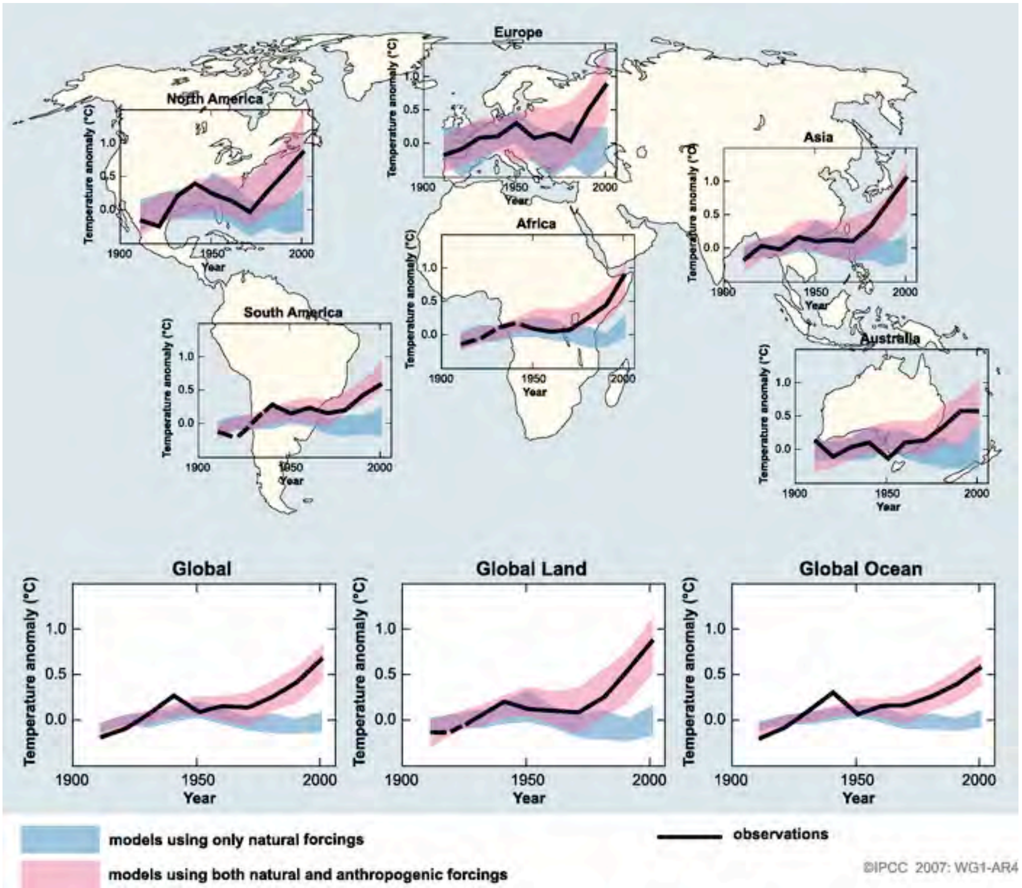


Fig. 6-22 Comparison of AR4 model predictions with and without greenhouse gas contributions for the 20th century for different regions of the world.

clearly do not fit the data. However, by the inclusion of greenhouse gas warming in the models, the experimental data (black lines), for the most part, fit within the red band experimental error limits for nealy all parts of the world and for different types of geographical features such as land and ocean.

Despite formidable problems with the General Ciculation Models, there have been some successes in predicting general weather trends and atmospheric movement, predicting the right average (greenhouse) temperature on Earth, and predicting specific trends in global temperatures. Models that factored in sulfate aerosols into its calculations did come very close to calculating the actual global temperature trends for the last century. This fit indicates a significant contribution of aerosols in the 1970s period where the global temperature graph was flat. The cooling effects of the volcanic eruption of Mt. Pinatubo in 1992 and 1993 on global weather were quantitatively predicted by these models. In effect, these volcanoes have been the some of the only "experiments" with which to test the models and especially the sensitivity to a clear climate forcing parameter.

Many predictions of global climate models that are currently being observed in what some scientists say are clear signals for global warming are: preferential warming in the Arctic, increases in sea levels, nights warmed more than days, winters warmed more than summers (consistent with increased outgoing IR absorption), more extreme precipitation events, more severe droughts during the warm season, an increase in above-normal temperatures, and a decrease in day-to-day temperature variability.

Problems encountered with the computer models

One of the biggest uncertainties in the General Circulation Models is how to model the formation and types of clouds. Because the physics and chemistry of cloud formation is uncertain at this time, the treatment of clouds in climate modeling is subject to much debate and experimentation. When cloud formation is excluded from models, there is general agreement among models. However, major differences among models arise because of different approaches to cloud formation.

As we have seen, the ocean has an immense capacity to absorb heat and carbon dioxide. Oceans are effective carriers of heat energy from the tropics to the poles. For many years, the dynamic nature of the ocean and its coupling to the atmosphere was not taken into account in general circulation models. When attempts were made to incorporate these complex interactions, some surprises surfaced. For example, the cycle time of this conveyor belt may be very slow. Much of the heavy, cold water in the lower reaches of the ocean floor may stay out of contact with the atmosphere for 500 to 2000 years. So when relatively warm water circulates into this region, its heat energy is dissipated in warming the ocean floor rather than being circulated to other parts of the surface. Thus global warming in the Northern Hemisphere, according to preliminary model calculations, may not spread to the Southern Hemisphere. In fact, the anticipated return to the surface in the 21st century of deep sea water cooled by the Little Ice Age (1450-1850 AD), may cause the temperatures to drop in the Southern Hemisphere at the same time as the potential warming of Northern Hemisphere occurs. Therefore, melting of the sea

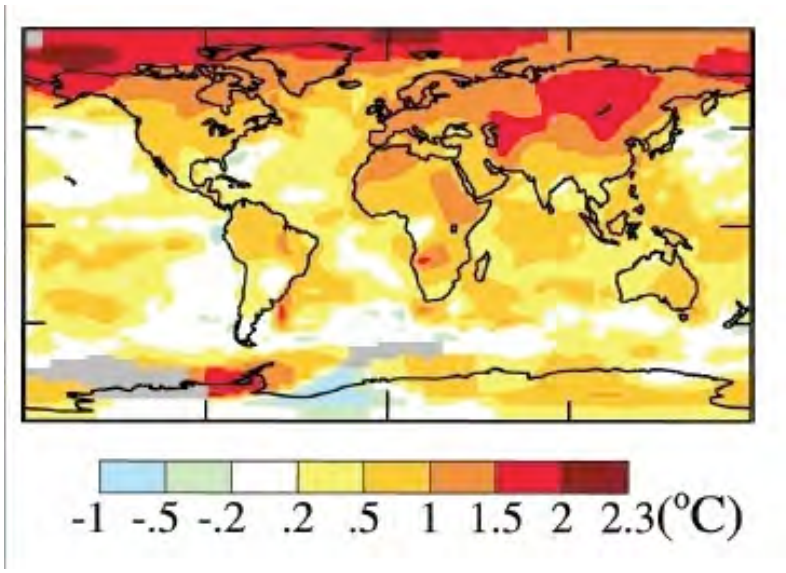


Fig. 6-23 Temperature increases or decreases for the period 2001-2007. Two trends are visible: (a) temperatures increased with lattitude in the Northern Hemisphere; (b) Arctic temperatures increased considerably more than in the Antarctic, leading to historic summertime melting.

ice around Antarctica may be less than anticipated, with a lower than predicted rise in sea levels from global warming.

A strong warming Arctic trend shown in Fig. 6-23 is predicted in all climate models. In fact, the trend has exceeded what these models predict. This is probably because of positive feedback effects. That is, the more ice that melts, the less reflective the remaining Arctic surface, causing more sunlight to be absorbed rather than reflected. This warms the air, which melts more ice, etc.

Heat and carbon dioxide exchanges with the ocean

The ocean is especially important because both heat and carbon dioxide are absorbed by it. Heat is transferred from the atmosphere to the ocean through molecular collisions between fast-moving atmospheric molecules, primarily oxygen and nitrogen, and the water molecules at the surface of the ocean. After collisions with water, many of the oxygen and nitrogen molecules give up excess energy, thereby cooling the air. These collisions induce faster vibrations of the liquid water molecules and therefore cause an increased molecular motion of water molecules at the water surface, which is reflected in higher water temperature. This heated water can either evaporate more water molecules or, if it is part of the conveyor belt, heat the deep ocean. However, net transfer of heat energy only occurs if there is a temperature difference between the water and the air. The rate of transfer of this heat energy depends on this temperature difference. Thus, the warmer the ocean is, the less effective a heat sink it is for warm air heat energy.

Carbon dioxide can dissolve in any water that is not already saturated with carbon dioxide. Momentary carbon dioxide dipole moments cause the gaseous CO_2 molecule to be attracted to the dipole moments of liquid water molecules at the surface of oceans and lakes and thereby are enticed into the liquid state, forming carbonic acid (H_2CO_3). The ionization reactions of the H_2CO_3 [reactions (6-3) and the reverse reaction in (6-5)] help keep the carbon in H_2CO_3 in solution.

The rate of entry of carbon dioxide and heat into the ocean is limited, even though the ocean's capacity for storing heat is great. Just as a stadium has the capacity to accommodate a large crowd, the rate of entry of fans is limited by rate of taking tickets at the gate. The "gate" in this analogy is the top layer of the ocean, which does not readily mix with the lower layers of the carbon dioxide poor ocean. Thus, a sudden surge of carbon dioxide and the resulting heat from global warming may strain the oceanic heat and carbon dioxide sink capacity of the ocean surface and provide a transient period in which these sinks are not able to respond quickly. It is estimated that for every metric ton (1000 kg) of fossil fuel carbon, 57% or 570 kg of carbon accumulates in the atmosphere. The other 43% is taken up by the ocean and land carbon sinks. This has been true over the period 1958-2000. However, deforestation also emits non fossil fuel CO_2 and adds uncertainty to this. A major focus of current research is the question of whether this fraction of 57% will remain constant in the future. Why worry about a constant fraction? Because sinks will probably saturate. With warming, the fraction of emitted fossil fuel CO_2 that accumulates in the atmosphere will increase as sinks saturate. The most recent records indicate that some saturation in beginning to occur.

Some predictions based on greenhouse warming indicate that more freshwater will move into the North Sea and may interrupt or slow down the Gulf Stream flow because the density of the water would be lowered below that necessary to help drive the conveyor belt. This could have two different possible consequences: one could be acceleration of the return of a European cold period, and the other could be a net heating effect due to lack of uptake of carbon dioxide in the atmosphere. Because the ocean is the repository of some 60 times the amount of carbon stored in the atmosphere, the temporary loss of this carbon dioxide sink could quickly increase the amount of carbon dioxide remaining in the atmosphere. Thus the ocean is a very important player in any climate change scenario and its role in global modeling is critical. The longer timescale processes like deep water formation and mixing of surface and deep ocean are important but long compared to the time scientists have been studying them.

Photosynthesis of microscopic oceanic phytoplankton initiate a complex life cycle that includes uptake of carbon dioxide. Upon their death, some carbon-containing plankton debris falls to the ocean floor, thus at least temporarily providing a net carbon sink. There is a very large potential for growth of these ocean plankton, provided the proper nutrients are available. In the Pacific Southern Ocean, there is a shortage of iron that limits the plankton growth. Experiments in which large quantities of iron have been added to several ocean test areas and stimulated increased growth of plankton, but these have not yielded promising results from an economic perspective. These plankton play an interesting role in the Gaia hypothesis that the Earth acts as a whole integrated ecosystem to adjust climate to maintain its current state.

——————————Linked material——————————

A natural source of sulfur dioxide is from phytoplankton in the ocean. Some phytoplankton in the ocean produce the gaseous waste product dimethyl sulfide, which is then emitted into the atmosphere from the ocean. Chemical reactions ultimately oxidize this compound into sulfate aerosols over the ocean that act as cloud formation sites. This series of chemical reactions is proposed as a potential negative feedback mechanism that tends to lower the temperature. Increased temperatures increase the biological activity and range of the phytoplankton, which yield larger amounts of dimethyl sulfide, which, in turn, yield larger amounts of aerosol and, therefore, more clouds, leading to lower temperatures. This is one

James Lovelock and a statue of "Gaia"

mechanism that James Lovelock, a British scientist, attributes to the concept of **Gaia**, in which the Earth reacts to such factors as greenhouse gases as a global entity (Gaia) to adjust climate and enable the global entity to survive in its current state more or less stabilized state. However, there is currently no evidence to confirm the importance of the importance of this process and therefore it is not included in climate models.

——————————End of linked material——————————

The carbon cycle and global warming

One of the most important components of the General Circulation Models is the treatment of the cycling of carbon atoms contained in atmospheric carbon dioxide. This **carbon cycle** represented in Fig. 6-24 tracks the changes in the chemical form of carbon in natural and anthropogenic cycles. Inventories of the various forms of carbon in the Earth must be made to be able to make these calculations. Recoverable fossil fuels contain an estimated 400 gigatons of carbon atoms (1 gigaton = 1 Gt = 10^9 tons = 1 billion tons). There are over 7 gigatons of carbon given off per year to the atmosphere. These come from fossil fuel burning (about 5.5 gigatons) and tropical forest deforestation (about 1.9 gigatons). Estimates of the uptake of carbon from the atmosphere by the ocean average around 3 gigatons per year. The net increase in the atmospheric carbon content of the atmosphere is about 3.4 gigatons per year. In the calculations of sources and sinks for carbon dioxide, there is a missing link. When the carbon dioxide taken up by the sea and the increased concentration of carbon dioxide are taken into account, there is about a gigaton of carbon in the yearly carbon budget that is taken up by processes that are incompletely understood.

Ch6/Oceans/p.3

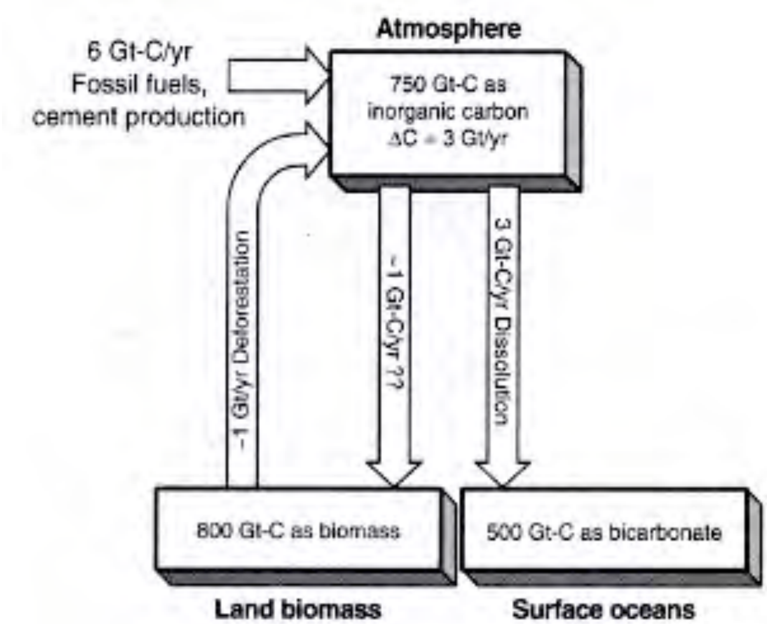


Fig. 6-24 Short term global carbon reservoirs and exchange rates that affect excess carbon generated by athropogenic activities. The measured rate of accumulation of carbon as CO_2 in the atmospheric reservoir is indicated as ΔC. (Gt = gigatons)
Turco, Earth Under Siege, Oxford, p. 374

There is much to be learned about the uptake and release of carbon dioxide from soils and other carbon dioxide sinks. Soil carbon has been called "the sleeping giant" in global warming because increased temperatures strongly increase the release of carbon dioxide by organisms decomposing soil organic matter. Increased releases of carbon dioxide from the soil and decaying vegetation could further raise the temperature, releasing more carbon dioxide in a positive feedback loop. Is the soil a net source of carbon or a net sink? Carbon dating studies are being used to help answer this question, but it is difficult to answer the global question because of the many different circumstances involving soils and vegetation. This is one of those hybrid climate change science areas where geology, biology, and chemistry are all needed to help answer the questions regarding greenhouse gases and potential global warming.

Methane has many different agricultural and biological sources. One worrisome source is the large amounts of methane "locked up" in solid methane hydrates at the bottom of the ocean where temperatures hover around 0ºC. Molecules of methane are surrounded in a water cage to give a solid that burns when heated and ignited. These hydrates are found in relatively shallow waters less than 2000 meters deep. Considerable thought has been put into mining these potential energy sources. Because some of these rather large deposits are found in warming Arctic waters, there have been concerns that these could cause sudden releases of methane, a potent greenhouse gas that could initiate a sudden warming event because of a positive feedback chain reaction. Studies of this problem report that there is no danger of this happening within this century. One hopeful sign is that the significant amounts of methane released during the 2010 Deepwater Horizon Gulf of Mexico Oil Spill apparently did not make it to surface. It is assumed that the methane was dissolved in the seawater and then consumed by bacterial blooms.

It has been assumed by many that the Amazon tropical forest is soaking up vast quantities of carbon dioxide because of the large amounts of vegetation being created However, there is debate over whether this vast ecosystem is a net source or a net sink of CO_2. This ecosystem is difficult to fully comprehend because of, among other complexities, the nature of the various ecosystem components, the naturally decaying vegetation that releases CO_2, and cyclic severe droughts that may be either part of natural climate variation or possibly weather patterns induced by global climate change. Further research is needed to more fully understand this highly important climate-influencing region.

The reconstruction of past climates reveals that the recent warming observed in the Arctic, and in the Northern Hemisphere in general, are anomalous in the context of natural climate variability over the last 2000 years. New ice-core records confirm the importance of greenhouse gases for past temperatures on Earth, and show that CO_2 levels are higher now than they have ever been during the last 800,000 years. Thus, it is important to take this very high carbon dioxide concentration seriously and try to predict its potential climate change consequences.

Global climate change: detection and attribution

The IPCC Working Group II "assesses the scientific, technical, environmental, economic and social aspects of the vulnerability (sensitivity and adaptability) to climate change of, and the negative and positive consequences for, ecological systems, socio-economic sectors and human health, with an emphasis on regional sectoral and cross-sectoral issues." Such studies make sure two steps are fully addressed in a scientific manner. This working group is very sensitive to the methods of detection and attribution of climate change impacts. It is important to this group that: (a) the change in a physical or biological process is statistically justified, and (b) that assignment of responsibility to anthropogenic causes is statistically sound. For example, climate-related changes in snow and ice in the **cyrosphere** (the portions of the Earth's surface where water is in solid forms such as ice, snow, and frozen ground) are often quite well recognized because ice and snow are so close to melting. Detection of such changes can be quantified in three ways: (a) rates of change and acceleration trends; (b) present conditions in relation to pre-industrial variability ranges; (c) spatial patterns of change as compared to modelled climatic scenarios.

One of the chief criteria in IPCC assessments is that all of the data must come from peer-reviewed journal reports. A glaring example of *not* following this criterion was in the AR4 report that stated that 80% of the Himalayan glaciers, source of drinking water for millions of Asians, would melt by 2035. In one section of this report, the following statement was made: "Glaciers in the Himalya are receding faster than in any other part of the world (see Table 10.9) and, if the present rate continues, the likelihood of them disappearing by the year 2035 and perhaps sooner is very high if the Earth keeps warming at the current rate. Its total area will likely shrink from the present 500,000 to 100,000 km^2 by 2035 (WWF, 2005)" This information conflicts with two other sections of AR4. An official IPCC retraction and correction has been issued. It turns out that the reference given was not from a refereed journal, but instead came from a 1999 interview with a single Indian glaciologist and reported by an environmental group "WWF," cited above. This statement should not have been in 2007 IPCC AR4. The error was fortunately caught and IPCC statement correcting the error was made in 2010. This was the only known error in the ~3000 page AR4 document. The major environmental impacts predicted in the AR4 document are summarized in Table 6-1

What is interesting about this error is that, since the IPCC retraction, there have been new published claims that one major group of Himalayan glaciers is actually advancing rather than retreating. One problem encountered is that a thin dark surface coating on some of these glaciers absorbs sunlight and promotes melting. This black soot is imported with other air pollutants from lower altitudes. However, one study indicates that if the surface coating is thick enough, it insulates the glacier and inhibits melting. If confirmed, this would makes complex calculations of future melting even more complex, since it brings in new uncertainties about the future status of soot-laden pollution into the calculations.

Predictions of future global temperatures and climate changes

The IPCC Fourth Assessment Report (AR4) concluded that "climate change has begun to affect the frequency, intensity, and length of many extreme events, such as floods, droughts, storms, and extreme temperatures, thus increasing the need for additional timely and effective adaptation. At the same time, gradual and non-linear change to ecosystems and natural resources and increasing vulnerability further increase the consequences of extreme weather events."

After being satisfied that the general climate models fit current and past global climate trends, modelers can venture to predict future climate trends. Tables 6-1 and Fig. 6-25 give the major IPCC predictions as of 2007. The next IPCC report will be issued in 2013.

Phenomenon[a] and direction of trend	Likelihood of future trends based on projections for 21st century using SRES scenarios	Examples of major projected impacts by sector			
		Agriculture, forestry and ecosystems [4.4, 5.4]	Water resources [3.4]	Human health [8.2, 8.4]	Industry, settlement and society [7.4]
Over most land areas, warmer and fewer cold days and nights, warmer and more frequent hot days and nights	Virtually certain[b]	Increased yields in colder environments; decreased yields in warmer environments; increased insect outbreaks	Effects on water resources relying on snow melt; effects on some water supplies	Reduced human mortality from decreased cold exposure	Reduced energy demand for heating; increased demand for cooling; declining air quality in cities; reduced disruption to transport due to snow, ice; effects on winter tourism
Warm spells/heat waves. Frequency increases over most land areas	Very likely	Reduced yields in warmer regions due to heat stress; increased danger of wildfire	Increased water demand; water quality problems, e.g., algal blooms	Increased risk of heat-related mortality, especially for the elderly, chronically sick, very young and socially-isolated	Reduction in quality of life for people in warm areas without appropriate housing; impacts on the elderly, very young and poor
Heavy precipitation events. Frequency increases over most areas	Very likely	Damage to crops; soil erosion, inability to cultivate land due to waterlogging of soils	Adverse effects on quality of surface and groundwater; contamination of water supply; water scarcity may be relieved	Increased risk of deaths, injuries and infectious, respiratory and skin diseases	Disruption of settlements, commerce, transport and societies due to flooding; pressures on urban and rural infrastructures; loss of property
Area affected by drought increases	Likely	Land degradation; lower yields/crop damage and failure; increased livestock deaths; increased risk of wildfire	More widespread water stress	Increased risk of food and water shortage; increased risk of malnutrition; increased risk of water- and food-borne diseases	Water shortages for settlements, industry and societies; reduced hydropower generation potentials; potential for population migration
Intense tropical cyclone activity increases	Likely	Damage to crops; windthrow (uprooting) of trees; damage to coral reefs	Power outages causing disruption of public water supply	Increased risk of deaths, injuries, water- and food-borne diseases; post-traumatic stress disorders	Disruption by flood and high winds; withdrawal of risk coverage in vulnerable areas by private insurers, potential for population migrations, loss of property
Increased incidence of extreme high sea level (excludes tsunamis)[c]	Likely[d]	Salinisation of irrigation water, estuaries and freshwater systems	Decreased freshwater availability due to saltwater intrusion	Increased risk of deaths and injuries by drowning in floods; migration-related health effects	Costs of coastal protection versus costs of land-use relocation; potential for movement of populations and infrastructure; also see tropical cyclones above

Table 6-1 Table SPM.1 from AR4 Working Group II showing some likely impacts of climate change projected from the various scenarios envisioned in Global Climate Models.

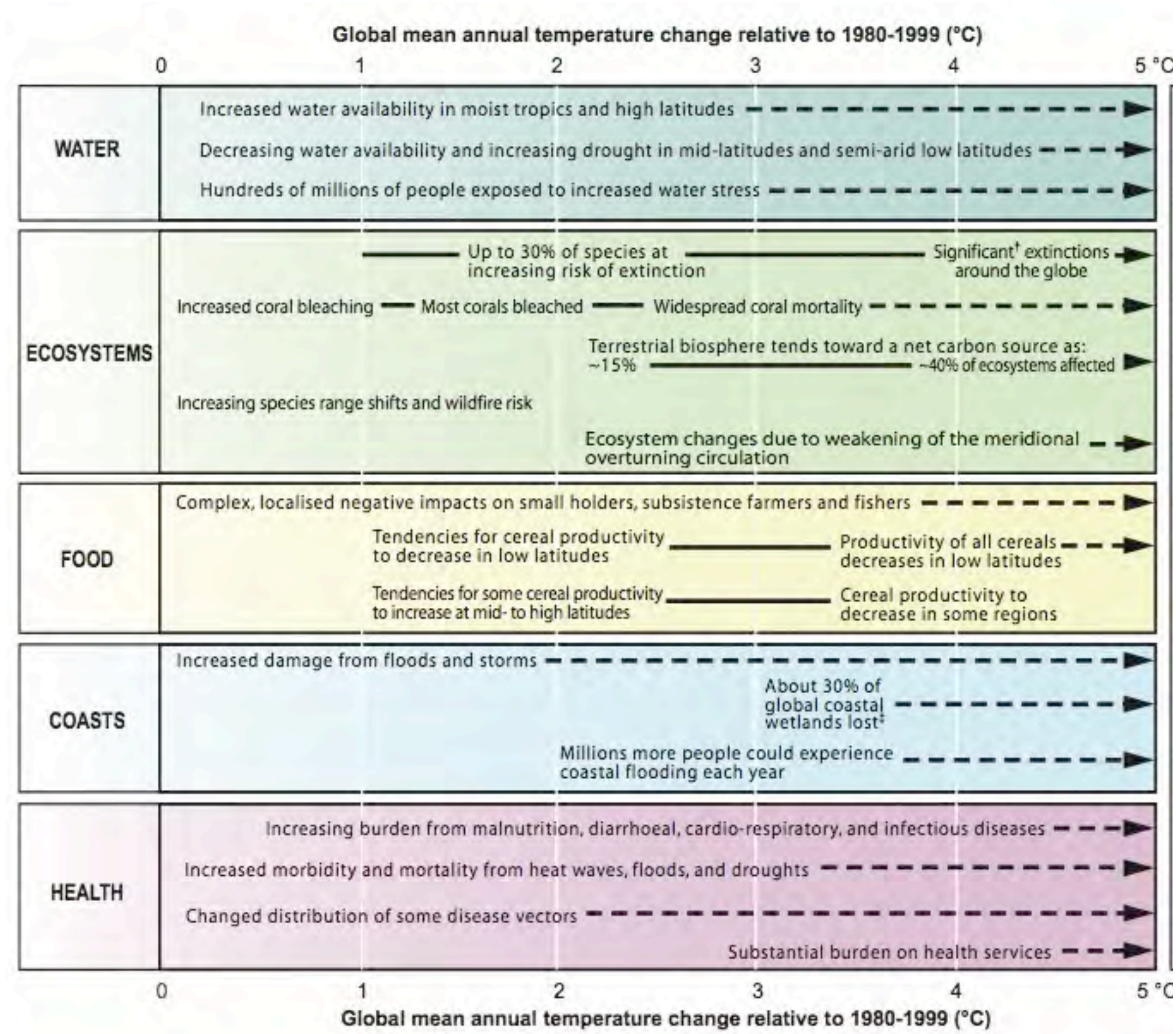


Fig. 6-25 Figure SPM.2 from AR4. Examples of global impacts projected for climate changes, sea level and atmospheric carbon dioxide assoicated with different amounts of global average surface temperature in the 21st century. The black lines link impacts, dotted lines onset of a given impact.

In preparation for the December 2009 United Nations Climate Change Conference in Copenhagen, a group of lead AR4 Group I authors prepared an interim report entitled "The Copenhagen Diagnosis 2009: Updating the World on the Latest Climate Science." While this report does not cover the latest published climate change papers, it is the latest collective summary representing a concensus of the published climate change literature as of 2009. Listed below is a summary of the principle points made in this summary:

• The Working Group I authors firmly stand behind the conclusions of AR4, most importantly that:

- For the next two decades, a warming of about 0.2°C per decade is projected for a range of Special Report on Emissions Scenarios (scenarios with a variety of different assumptions). Even if the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels, a further warming of about 0.1°C per decade would be expected. This conclusion is an indication of what is called climate change "commitment" or inertia. That is, the excess CO_2 would not quickly be absorbed by the carbon sinks (ocean and land, for example). The world is commited to further climate change no matter what it does because of past greenhouse gas emissions that are still found in the atmosphere and will be for the near future. It's only the extent of the change that can be negotiated at this point by conscious mitigation actions. (Basically, it's like a fully loaded oil tanker that is ordered to stop and turn around. It will take a while! A lot longer than for the tanker!)

- Continued greenhouse gas emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would very likely be larger than those observed during the 20th century. (Continuing the oil tanker analogy, with greater speed, it will be much more difficult to stop or turn around the tanker.)

- There is now higher confidence in projected patterns of warming and other regional-scale features, including changes in wind patterns, precipitation and some aspects of extremes and of ice cover. (With the oil tanker analogy, if we spot an iceberg ahead, the faster we go, the more certain we know that we can't avoid the iceberg.)

- Anthropogenic warming and sea level rise would continue for centuries due to the time scales associated with climate processes and feedbacks, even if greenhouse gas concentrations were to be stabilized. (For the tanker analogy, its rudder maneuverability at this speed and its bulk weight limits what we can do to avoid any icebergs in the near future. We can only make sure that the lifeboats are at the ready.)

In addition, the Copenhagen Diagnosis stresses the following conclusions:
• The combination of observations and paleoclimate information shows unprecedented changes in the climate system, both in amplitude and rate for hundreds to many thousands of years;
• Wide-spread melting of ice margins is observed in Greenland and Antarctica with implications for sea level rise;
• Emitted CO_2 remains in the atmosphere for thousands of years causing irreversible changes in the climate and in ocean chemistry;
• Geoengineering methods will not mitigate the direct effects of CO_2 increase. This is because of the persistence of the high CO_2 concentrations despite any mitigation strategy short of somehow extracting the CO_2 from the atmosphere.

Thus far, climate change models have predicted well the measured increases for the past twenty five years in global temperatures based on greenhouse gas concentrations (0.19 ºC per decade). The one uncertainty in setting the variables for long range projections is future greenhouse gas concentrations. Thus, multiple scenarios are modeled ranging from extrapolating current trends of growth in greenhouse gas concentrations into the future with no future reductions to a series of scenarios in which CO_2 concentrations are reduced over time.

It is surprising to see predictions when the CO_2 emissions are cut to zero. Because of the slow oceanic uptake of the CO_2 already present in the atmosphere, this excess greenhouse gas continues to warm the atmosphere and cause adverse climate changes. We are "commited" to future climate change, no matter how drastic our efforts to cut back CO_2 emissions.

If we examine the other extreme of continuing with the current trends of greenhouse gas concentration growth, we again confront discomforting predictions. Because of positive feedback loops of the types discussed above, the predictions are that a delay in cutting back on greenhouse gas emissions risks irreversible damage to many of the world's ecosystems. Global temperatures are predicted to increase beyond what is "acceptable" temperature increases that can reasonably handled. Global flooding of up to 7 meters would cause many millions of environmental refugees having to flee their contries.

According to the 2009 Copenhagen Diagnosis: "Global mean air-temperature is projected to warm 2°C – 7°C above pre-industrial by 2100. The wide range is mainly due to uncertainty in future emissions. There is a very high probability of the warming exceeding 2°C unless global emissions peak and start to decline rapidly by 2020. Warming rates will accelerate if positive carbon feedbacks significantly diminish the efficiency of the land and ocean to absorb our CO_2 emissions. Many indicators are currently tracking near or above the worst case projections from the IPCC AR4 set of model simulations." Thus, there is a large potential for abrupt change and irreversibility in the climate system according to these calculations and predictions.

Future tipping points

One way of thinking of a tipping point or threshold is that point at which there is a transition from one stable state to another stable state. For example, consider our current climate state to be a wine glass half full of wine and, after reaching and passing the tipping point, that same wine glass after it has been tipped over. There are a number of states in which the wine glass can be slightly nudged and it returns to an upright position. However, there are many more ways in which energy can be applied to the glass to make it irreversibly move to the other (nominally) stable state of spilled wine and possibly broken glass. The process is irreversible after reaching the tipping point and it is nearly impossible to return to the upright half-filled wine glass state.

According to the 2009 Copenhagen Diagnosis, there are several elements in the climate system that could pass a tipping point this century due to human activities, leading to abrupt and/or irreversible change. 1 °C global warming (above the 1980-1999 average temperature) carries moderately significant risks of passing large scale tipping points, and 3 °C global warming would give substantial or severe risks. There are prospects for early warning of approaching tipping points, but if we wait until a transition begins to be observed, in some cases it would be unstoppable. “If global warming is to be limited to a maximum of 2ºC above pre-industrial values, global emissions need to peak between 2015 and 2020 and then decline rapidly. To stabilize climate, a decarbonized global society – with near-zero emissions of CO_2 and other long-lived greenhouse gases – needs to be reached well within this century. More specifically, the average annual per-capita emissions will have to shrink to much less than1 metric ton CO_2 by 2050. This is 80-95% below the per-capita emissions in developed nations in 2000.”

One climate expert, James E. Hansen, believes that such a tipping point – 350 ppm CO_2 – may have already been surpassed. Others believe that, though we have already passed that CO_2 concentration, we must take this opportunity to lower the existing carbon dioxide concentration back to 350 ppm before it is too late.

Mitigation of greenhouse gas-induced climate change effects; Geoengineering

Is there anything that can be done, other than reducing the output of greenhouse gases, to reduce or counterbalance the effects of anthropogenic climate change? There have been a number of ideas proposed for climate change **mitigation**, defined as the action of reducing the severity, seriousness, or painfulness of something. Some of these mitigation schemes are broadly classified as geoengineering climate change solutions. Each of these proposals has associated with it certain risks, primarily because they would have to be done on a large scale, with many unknown potential consequences.

One natural and one anthropogenic previous cooling event suggest that the ingredients for atmospheric aerosols might be injected into the atmosphere to reflect sunlight back into space, thereby cooling the Earth. The massive eruption of the Mt. Pinatubo volcano in 1991 caused a fairly small, but statiscally significant, global cooling. There were large amounts of SO_2 gas spewed into the stratosphere during this eruption along with other gases and particles. Computer models were used to predict the amount of cooling and were in good agreement with the trend (Fig. 6-26). Large quantities of SO_2 were injected into the atmosphere by burning high sulfur-containing coal during and before the 1970 period correspondiing with a cooling trend, presumably because of the sunlight-reflecting aerosols formed. Successive efforts to remove the SO_2 by smokestack scrubbing ultimately reduced sulfate aerosol formation, allowing the greenhouse gas-induced global warming to dominate.

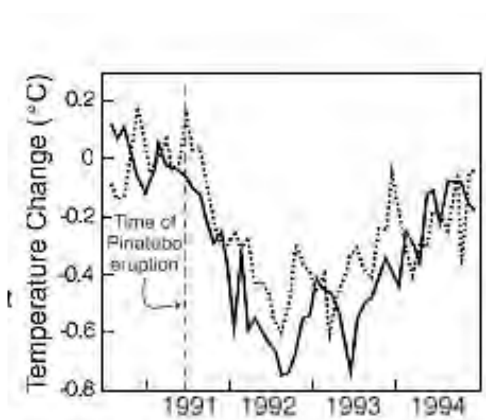


Fig. 6-26 Average global temperature change following the explosion of Mt. Pinatubo.

Thus suggestions have been made to deliberately inject SO_2 into the stratosphere to form aerosols to counteract global warming. The big unknown with this suggestion is the unintended consequences of such action. One problem with this mitigation technique is that regardless of its success or problems, there would need to be replenishment of this SO_2 for long periods of time. This is because the sulfate particles would probably settle. Another one is stratospheric ozone depletion – aerosols in the lower stratosphere and heterogeneous chemistry caused the largest ozone depletion at midlatitudes in the lower stratosphere after Pinatubo. The climate system is complex and geoengineering risks unintended consequences. In any case, the excess CO_2 causing the climate change would remain in the atmosphere for many hundreds, if not thousands of years.

There are many other proposed mitigations similar to that described above, but only one really apparently solves the problem: safely reducing the concentration of CO_2 in the atmosphere to scientifically acceptable levels. What are these levels? A concensus among scientists doing computer modeling is reducing the CO_2 level to approximately 350 ppm CO_2 before the year 2040. This would presumably make the probability less likely of reaching a tipping point of irreversible global climate change. There are also economic mitigation actions such as carbon tax that encourage actions to mitigate climate change.

Adaptation to climate change

Suppose the tipping point has already been reached? There are those who might acknowledge this and pending irreversible climate change, but claim that civilization has adjusted to change in the past and can do so again in the future. Will not life be easier with less winter storms and a warmer climate? There are a number of issues that this argument raises. How fast is the change? What is the degree of the change? What parts of the world will be most affected? How will they be affected?

Consider the Pacific Islanders whose land is already beginning to be inundated by rising sea levels. They have no choice but to migrate, and some are already being forced to do so. Those who occupy seaside or flood prone homes close to sea level may live in densely populated areas, where migration is not only inconvenient, but politically difficult to impossible because of the large numbers of forced migrants involved. Such is probably the case with Bangladesh as well as perhaps certain areas in southern Florida. Large metropolitan seaport or coastal cities face the challenge of building seawalls that will withstand both the increasing sealevels and increased storm surges. In some cases, such as large sea level rises, sea walls may not be feasible. Preservation of wetlands and beach areas will be a challenge.

What about animal life and climate change? Changes in habitat range are already being observed with many different forms of wildlife. Bird ranges are moving north during the winter months in the Northern Hemisphere. There is talk about planning climate change migration paths for larger wildlife. However, necessary ecosystems may not be able to keep the same pace with animals as the climate changes.

Some wild plants can and have migrated following climate changes, but it looks as though such changes may accelerate in the near future. Many plants and trees cannot migrate for a number of different reasons, including those previously listed. In all instances previously listed, the degree of adapability will depend on the severity of the climate change, which at present is unknown.

International and US actions on greenhouse gas emissions

In 1992, the United Nations Framework Convention on Climate Change was held in Rio de Janeiro. This general conference led to a series of meetings culminating in the 1997 Kyoto, Japan, conference following the 1995 IPCC report suggesting the probable effects of humans on global climate. At this conference 160 nations signed an historic protocol to the 1992 Framework Convention in which specific measures were undertaken to reduce greenhouse gas levels. Targets were set, timetables, reporting requirements, and trading mechanisms were set and the responsibilities for enacting new policies to meet these goals were left to national governments. The target for the US was to reduce CO_2 levels to those of 1990. Thus far few industrial nations have met their targets. The Clinton administration signed the Kyoto protocol, but did not submit it to the US Senate for ratification because of its likely defeat. The Bush administration withdrew from the Kyoto protocol. The Obama administration has begun negotiations but with no binding commitments.

The "Debate"

There is an influential minority of scientists and nonscientists, most of whom are not actively doing research in climate science, who believe that there is insufficient scientific evidence to cut back CO_2 emissions or who question some of the prevailing scientific theories regarding global change. Some welcome the greenhouse warming because they believe it will enhance agriculture and the quality of life of those in the colder regions. Some oil companies maintain that the case that burning fossil fuels have contributed to global warming is not proven. They resisted the Kyoto protocol recommendations because underdeveloped nations were exempted from restrictions on CO_2 levels. They claimed that we had more time to refine the atmospheric science and to make further measurements before making drastic cutbacks.

The vast majority of scientists who are working in the field of global change support the Kyoto protocol. 2600 of these scientists signed a statement supporting strong action prior to the Kyoto meeting. In answer to the criticism of potential economic damage because of cutbacks in fossil fuel burning, one scientist replies "can the world stabilize climate before climate destabilizes the economy?" Another states that "altering the composition of the atmosphere is a momentous but rather unwanted accomplishment."

Some of these scientist liken the unprescedented rise in world CO_2 concentration to a “one rat experiment” with the world that’s never been done before. This is one experiment whose outcome is unknown and will not be repeatable. A possible negative outcome in this experiment is suggested by most scientists because of its potentially irreversible nature. It has been reported that some scientists involved with the IPCC think that the world has its foot on the CO_2 accelerator and that easing up slightly will not avoid the consequences of the speeding climate change.

The feelings of many supporters of the Kyoto protocol are represented by Wallace Broecker, the scientist who first suggested the idea of an ocean conveyer belt. He believes that the “climate system is an angry beast and we are poking at it with sticks.” He suggests that sudden changes in global temperature may very well lead to a shutting down of this ocean conveyer belt in a very short time period, possibly as little as a decade, with potentially serious and sudden consequences, a “flicker in climate.” One possible consequence of this would be, he suggests, a potential disaster for world agriculture, perhaps at a time when world population will have doubled.

Personal decisions regarding global warming

What can I do, if I believe there is a danger of global warming?

We have presented evidence indicating that accelerated global warming and resulting climate change have indeed occurred within the past century. We have also presented the case that there is credible evidence and overwhelming scientist support for the idea that there is a human influence responsible for this trend. What can be done about this? You and others like you will have to decide on future courses of action, both at the local and at the national levels. If you feel that society cannot afford to wait for concrete evidence of such a correlation, there are steps that you, as an individual can take to aid in avoiding the potential problems alluded to in this chapter. The problem can be approached on a case-by-case basis, depending upon the greenhouse gas:

1) Carbon dioxide: stabilize or reduce the burning of fossil fuels (coal, oil, natural gas) and the burning of non-renewable biomass resources (tropical forests) and substitute, wherever possible, renewable energy sources that do not increase the global atmospheric concentration of CO_2 Improve efficiencies for fossil fuel power generation and conserve heat energy (Chapter 11).

2) Methane: find ways to eliminate methane coming from marshlands (without destroying wetlands), change methods of rice farming, cut down on landfills and tropical deforestation, raise fewer cows, and cut methane losses during fuel production and from leaking natural gas pipelines.

3) Nitrous oxide: cut down on fertilizer use, coal combustion, high temperature combustion processes, tropical deforestation, and agricultural waste.

4) Chlorofluorocarbons: reduce or eliminate the manufacture of HCFCs. Make sure that HCFC substitutes have the lowest possible greenhouse potential (Chapter 7).

In 2007, the IPCC declared that human activities are almost certainly responsible for at least part of the global warming measured during the past century. Since then, in the peer reviewed scientific literature, there has been no credible scientific evidence to counter this conclusion. On the contrary, the evidence seems to be that the trends are more along the worst case scenarios considered by the IPCC, with some trends even worse than the worst case scenario.

If CO_2 is the most critical greenhouse gases, as it seems to be at the present time, then action means reducing the use of fossil fuels for power generation and transportation and finding alternatives to these. Consult Chapter 11 of this text for concrete suggestions in this respect.

The impacts of global warming and climate change depend on the extent of the warming and are uncertain. Very high global temperatures could theoretically: cause coastal flooding, cause drastic changes in climate, cause some fertile regions to be turned into deserts, and extend tropical regions into regions currently having more moderate climates. A number of atmospheric scientists maintain that the ever-increasing concentration of greenhouse gases is sufficient to create a significant potential for disaster ahead. They claim that it is important that we cut back now before it is too late to take remedial action. The decision on what to do is rapidly becoming not just a scientific, but also a political one. Thus the scientific problem of climate change now becomes, in addition, one of science policy. In other words, it's a personal decision, namely yours and how you interact with your government on an important scientific issue.

Meanwhile *be sure to access our Website Update to review the latest information on this continuing problem*.

Summary

1. What is the mechanism of the greenhouse effect?

   The greenhouse effect arises from the energy of that portion of the sunlight that is absorbed by the Earth and is then reradiated as long wavelength infrared radiation. Clouds and greenhouse gases absorb this infrared radiation, and then reradiate part of this radiation energy back toward the Earth, thereby trapping heat energy from the Sun and increasing the global temperature by about 30°C

2. What are the characteristics of photons?

   Photons are wavelike particles of energy that have both electric and magnetic dipole character and that oscillate with a characteristic frequency. Photons can have many different frequencies spanning the electromagnetic spectrum from the very highest frequency gamma rays through ultraviolet and visible light to infrared, microwaves, and radio waves at the low frequency end of the spectrum.

3. What do photons and molecules have in common?

    Molecules translate through space and undergo interatomic vibration and molecular rotation. Photons oscillate in their electrical and magnetic properties with different frequencies. Thus, they both have cyclic oscillations with certain frequencies. They both have electrical properties that are associated with these oscillations.

4. Why might an infrared photon interact with a greenhouse gas molecule?

    Selective interaction of an oscillating molecular dipole with the oscillating electric dipole associated with the infrared photon causes complete absorption of the photon. Symmetrical molecules, such as carbon dioxide and methane, are greenhouse gases because of asymmetric vibrations leading to oscillating dipoles. O_2 and N_2 do not absorb IR photons and are therefore not greenhouse gases.

5. What is the historical connection between global temperature and greenhouse gas concentrations?

    Ice core data suggest that, for many hundreds of thousands of years, global temperatures have risen and fallen in conjunction with increases and decreases of greenhouse gas concentrations. During the past century, the Earth has warmed about 0.5°C, although there was at least one 30 year period where there was a lack of warming. Greenhouse gas concentrations have risen markedly in the last century after having remained essentially constant over the last thousand years, raising the possibility of significant global warming in the future because of expected future rises in greenhouse gas concentrations.

6. What are the reasons to think that rising greenhouse gas concentrations may have detrimental consequences on global climate?

    Infrared radiation emitted by the sun-warmed Earth will be trapped more efficiently because of the greenhouse effect, causing a rise in global temperature. Increased temperature will evaporate more surface water, forming water vapor molecules with additional energy, which is released to the atmosphere when precipitation forms, increasing the severity of weather systems.

7. What are the assumptions and limitations of computer models that predict future global temperatures.

Scientists have created computer models that incorporate numerous parameters that affect weather and have attempted to calculate global temperature trends into the past, with some success, and to predict warming trends in the future. Predictions from these models indicate that future warming will be anywhere from 1°C to 6°C by 2100. The accuracy of these forecasts is uncertain and the steps to be taken by society because of them is a subject of much controversy. However, the scientists who are engaged in climate research are nearly unanimous in their warnings of pending serious problems that will lead to damaging climate change unless greenhouse gas emissions are not cut back drastically.

8. What are the definitions of the following climate change terms: climate forcing, feedback, and impact?

Climate forcing is an event that interacts with a global climate that is initially in a global energy input-output equilibrium, thereby disturbing that equilibrium. For example, increased sunlight from the Sun flowing into the Earth would cause a climate forcing. Climate feedbacks are Earth processes that amplify or dampen a climate forcing. Climate impact is the net result of climate forcing and feedback, for example, increased global temperature, melting of polar ice sheets, etc.

9. What is the nature of the controversy regarding global climate change?

There is a strong concensus among thousands of IPCC climate scientists that there is a human-caused global warming component that could lead to dangerous climate consequences. The "controversy" is primarily generated by scientists and non scientists who are not currently active in climate research. The concensus is based on peer-reviewed scientific journal publications. The opposition to this consensus is not based on peer-reviewed scientific journal publications.

Review Questions

1. What is the difference between the greenhouse effect and global warming?

2. Describe characteristics of a photon that change as it moves through space.

3. Discuss the possible fates of a single visible light photon, and the energy contained in that photon, as it moves from the sun to the Earth's surface.

4. Indicate which types of photons in the electromagnetic spectrum have the highest frequency and which have the longest wavelength.

5. Which has the higher energy, an infrared or an ultraviolet photon?

6. How does visible sunlight warm the Earth's atmosphere?

7. How does infrared radiation from the earth warm the atmosphere?

8. Water and carbon dioxide are both greenhouse gases. Why is one a desirable and the other a potentially harmful greenhouse gas?

9. How are experiments with ice cores able to reveal greenhouse gas concentrations over the past 150,000 years? What correlations are observed in these experiments?

10. What is thought to be responsible for the cyclic nature of the Earth's ice ages?

11. What is unusual about the magnitude of the current concentrations of the greenhouse gases carbon dioxide, methane, and nitrous oxide (considered over the recent history of the Earth)?

12. Characterize the global temperature trends shown in Figure 6-11 in your own words.

13. Are all greenhouse gas molecules equal in their effectiveness in absorbing infrared radiation? If not, what characteristics cause a given molecule to be a more efficient absorber?

14. What are the strengths and weaknesses of current global warming models?

15. Discuss the role played by clouds in warming and cooling of the Earth.

16. What is a general circulation model? What are its drawbacks, its successes, and its failures?

17. For what reasons are the treatment of clouds and cloud formation so critical in theoretical modeling of global warming?

18. General circulation models were not considered sophisticated until interactions between the oceans and the atmosphere were included. What types of interactions must be included for global warming calculations?

19. What drives the "belt" in the great ocean thermohaline conveyor belt? How could increases in greenhouse gas concentration affect this system?

20. What molecular properties cause carbon dioxide to dissolve in liquid water? What might limit the solubility of carbon dioxide in the ocean?

21. Suppose a given amount of carbon dioxide is to be delivered to the atmosphere by burning fossil fuel. From an environmental point of view, is it better to spread out the delivery of this amount of carbon dioxide over a short or a long period of time? Why?

22. Some scientists are concerned about the decreasing salinity of the ocean off the coast of Greenland. Why worry about how salty an ocean is?

23. What are the effects of volcanoes on the average temperature of the Earth? What about the effects of anthropogenic sulfate aerosols?

24. Some scientists predict that the drive to cut air pollution may lead to an acceleration of global warming. How could this be?

25. What is a positive feedback effect? Give an example from your knowledge of greenhouse gases.

26. Name several sinks for carbon dioxide other than the ocean. Name several sources of carbon dioxide besides fossil fuel burning.

27. In what way might the theory of chaos be related to global warming?

Problems

28. Which photon has a longer wavelength, an infrared or a gamma ray photon?

29. Which of the following photons travels fastest through air: a radio wave, green light, an X-ray?

30. In what specific manner do you think each of the following photons might react with a carbon dioxide molecule: an infrared photon, a photon of visible light, an ultraviolet photon. Repeat the exercise using a water molecule.

31. Water in clouds absorbs infrared radiation (IR). Water vapor in the atmosphere consisting of gas phase water molecules also absorbs IR photons. What might be: (a) the differences in the mechanism of absorption in these

two cases, and (b) the net result of the absorption.

32. Are oxygen (O_2) or nitrogen (N_2) in the atmosphere greenhouse gases? How about NO, CH_4 and CFCs?

33. What happens to a molecule that emits an infrared photon? In such a case, what do you think would be the relationship between the leaving IR photon and the molecule that just emitted the photon? (Make an intelligent guess based upon the reaction between an incoming photon and an absorbing molecule.)

34. Which of the following molecules would have a permanent dipole moment: HCl, N_2, CO, NO_2, CH_3Cl? Each of these is a gas at room temperature. Can they be greenhouse gases? What are the Lewis structures of each?

35. What type of vibrational and/or rotational modes of the above molecules in question 35 above would give rise to oscillating dipole moments?

36. Criticize or justify each of the following statements:

    (a) Because the carbon dioxide concentration of the world's atmosphere is increasing, there must be a corresponding increase in the average temperature of the world.

    (b) The reason for record temperatures during the past ten-year period is definitely the greenhouse effect.

    (c) Concentrations of CFCs are much lower than those of carbon dioxide in the atmosphere. Therefore, CFCs do not contribute to the greenhouse effect as much as carbon dioxide.

37. Explain what happens when a photon is: (a), absorbed by a carbon dioxide molecule, and (b), emitted by the same molecule.

38. Can a visible photon be absorbed by an isolated water molecule in the gas phase?

39. Contrast methane and CH_3Cl in terms of: being a greenhouse gas, having a permanent dipole moment, and motions that might give rise to an oscillating dipole moment.

40. Fossil fuel burning is adding approximately 5.3 gigatons of carbon (as CO_2) to the atmosphere every year. How much of this carbon remains in the atmosphere and how much is taken away by various sinks? What are the most important sinks?

Discussion Questions and Group Projects

41. Suppose that a recent news story indicates that the most sophisticated general circulation climate model predicts a global warming of 13°F by the year 2025. What thoughts should run through your mind at this revelation? What actions should you take?

42. Contrast the potential effects on global warming of using each of the following pairs as energy sources: wood vs. coal; coal vs. oil; wind power vs wood. Think of other contrasting pairs and repeat the exercise.

43. Discuss the pros and cons of reducing the use of fossil fuels and CFCs in terms of the potential effect on possible global warming in the future.

44. Discuss the validity of the statement: "Carbon dioxide is a greenhouse gas. Carbon dioxide concentrations have increased significantly in the last fifty years along with average world temperature. Therefore the increase in the average world temperature is due to the greenhouse effect. It's perfectly logical!"

45. Are we due for an ice age or for global warming in the 21st century?

46. Think of ways in which you generate greenhouse gases because of your activities and ways in which you can cut back on these activities. Would it be worthwhile to do so?

47. Search the Internet and your library for information on the following topics: greenhouse gases, greenhouse effect, and global warming. In particular, look for information and views expressed that differ with those found in this text. Point out these differences to your instructor, making sure to record the URL or other source, or copy the information along with its source directly, if possible.

Readings (to be updated later)

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