Fig. 10.1. Greenhouse warmings of Mars, Earth and Venus are about 5°C, 33°C and 500°C.

Chapter 10. Runaway Greenhouse

Mars, Venus and Earth are the Goldilocks planet -- too cold, too hot, and just right. These planets nicely show how the greenhouse effect depends on atmospheric composition.

Physics of the greenhouse effect is mainly energy balance: a planet sends back to space, in the form of heat radiation, the same amount of energy that it absorbs from sunlight. The amount of absorbed solar energy is known for each planet – from the Sun's measured irradiance[1] and the planet's measured albedo, which is the fraction of incident sunlight that the planet reflects away. Absorbed solar energy is the remaining fraction of the incident solar radiation.

Radiant energy leaving a surface increases as the surface temperature rises. The radiated energy as a function of the temperature is defined by the Stefan-Boltzmann 'law' (physical principle), which was deduced by Josef Stefan in 1879 from laboratory measurements of the Irish physicist John Tyndall and independently derived from thermodynamic theory by Ludwig Boltzmann in 1884. The equation[2] expressing this law makes it easy to calculate the planetary surface temperature required to radiate back to space the absorbed solar energy.

If the planet has an atmosphere that absorbs heat (infrared) radiation, calculation of the surface temperature is more complex. The atmosphere acts like a blanket – it reduces heat radiation to space. The atmosphere itself radiates heat to space, but the atmosphere transfers a reduced amount of heat, because the atmosphere at altitude is usually colder than the ground, where most solar energy is absorbed. Thus, when more greenhouse (heat absorbing) gas is added to the air, radiation to space is reduced and the planet temporarily is out of energy balance – more energy coming in than going out -- so the planet gradually warms until energy balance is restored.

The processes discussed so far constitute 'radiative transfer' of energy. Radiative transfer alone is inadequate to describe atmospheric temperature, because atmospheric motions also transfer energy. Heating of the ground, for example, produces hot air, which rises, just as a hot air balloon rises. Convection, this vertical mixing of air and heat, can be included readily in calculations of the vertical temperature profile in the atmosphere.

A still more realistic calculation accounts for three-dimensional energy transfer. Solar energy, absorbed more at low latitudes, is carried poleward by winds, and by the ocean on Earth. To handle all that, we need a global climate model. However, the simple one-dimensional radiation plus convection calculation is sufficient for good understanding of the greenhouse effect.

Mars' atmosphere is so thin that almost all of the heat radiation from the ground goes straight through the atmosphere to space. As a result, Mars' surface temperature is only a few degrees warmer than the temperature calculated by the Stefan-Boltzmann law. Specifically, Mars requires a surface temperature of only about minus 50 degrees Celsius (-50°C) in order to radiate back to space the energy that it absorbs from the Sun. The temperature -50°C is about 60 degrees below zero Fahrenheit (-60°F). Mars is too cold for Goldilocks or any bear.

Earth has more atmosphere than Mars. John Tyndall meticulously measured the radiation properties of many gases.[3] He found that the main constituents of Earth's atmosphere, the diatomic molecules nitrogen (N_2) and oxygen (O_2), are transparent to visible light and infrared radiation, but the triatomic molecules, water vapor (H_2O) and carbon dioxide (CO_2), are strong absorbers of infrared radiation.[4] We will learn more about the remarkable Tyndall later.

Earth absorbs 70% of the energy it receives from the Sun. If Earth had no atmosphere, its temperature would need to be about -18°C (about 0°F) to radiate that amount of energy back to space, according to the Stefan-Boltzmann law. In reality, Earth's average surface temperature is a pleasant +15°C (59°F). So Earth's greenhouse effect is 33°C (almost 60°F).

Venus absorbs only 23% of incident sunlight, because of its highly reflective, complete cloud cover. As a result, it requires a planetary radiating temperature of only -45°F (-43°C) to radiate that energy back to space. However, the Venus surface temperature is more than 450°C, hot enough to melt lead! The greenhouse effect on Venus is about 500°C (900°F)!

The main reason for the huge greenhouse effect on Venus was revealed by the Soviet Venera spacecraft and the later United States Pioneer Venus mission. The surface pressure on Venus is about 90 bars, which is 90 times the surface atmospheric pressure on Earth, and atmospheric composition is almost entirely CO_2. Other constituents, mainly a small amount of water vapor, the sulfuric acid clouds, and sulfur dioxide (SO_2), contribute to the greenhouse effect, but CO_2 is responsible for most of the greenhouse warming on Venus.[5]

The Goldilocks planets illustrate weak, moderate and strong greenhouse effects. But how did the planets get to the present situations? What are the implications for future climate on Earth? Can Earth end up like Venus, as a lifeless hothouse? Yes, it can, but the runaway greenhouse story described in *Storms of My Grandchildren* requires a modification.

Venus suffered a runaway greenhouse effect that reached a terminal state, the 'baked crust' greenhouse. Baked crust? How does that work? Venus was doomed to a baked crust, and a permanent climatic hell, as soon as it lost its ocean. But wait, let's back up a step first.

The crust is the outer layer of a 'solid' planet such as Venus or Earth, like the skin on an apple. Continents are tectonic plates, slabs of solid rock, which are mobile, riding on top of the viscous mantle. South and North America, for example, are sliding westward at a rate of about an inch per year, overriding thinner oceanic crust that lies under the Pacific Ocean.

Volcanoes and mountain building occur along the forward edges of the continental plates, continually pouring volatile crustal gases, including CO_2, into the atmosphere. On a planet with an ocean, the CO_2 gets put back into the crust rather quickly – that is, if you consider a few thousand years to be quick, which it is for a planet billions of years old. The mechanism extracting CO_2 from the air is chemical weathering – streams and rivers carry chemicals to the ocean, ultimately depositing CO_2 as limestone on the ocean floor. (Later we will discuss enhanced weathering as a way to speed up removal of human-made CO_2 from the air.[6])

On a planet without an ocean, like the Venus of today, CO_2 from volcanoes stays in the air, building up to a huge amount – the crustal CO_2 is thus 'baked' into the atmosphere. There is so much CO_2 in the air that the surface pressure, 90 times that on Earth, would crush a human being, if he or she were not already fried to a cinder!

How did Venus lose its ocean? Will Earth lose its ocean? Yes, it will, but not soon. The story is pretty easy to understand.

Our Sun, and the planets orbiting about it, formed 4.6 billion years ago from the gravitational collapse of a swirl of gas, ice and dust in a spiral arm of our Galaxy, the Milky Way. Initially the planets all had similar compositions, but the inner planets – Mercury, Venus, Earth and Mars – lost most of their gases because of their small planetary masses and proximity to the Sun. [Planetary formation is discussed further in the Galileo chapter of Battleship Galactica.]

Atmospheres of the inner planets are believed to be mainly secondary. Radioactive heat is sufficient for the planetary mantle to behave as a viscous fluid on geologic time scales and release volatile gases, especially from volcanoes. Young Earth, because of its larger mass and greater distance from the Sun, had more water than young Venus.

Young Venus had enough water to form an ocean, but lost most of its water through hydrogen escape. Air molecules continually bump into each other, moving faster when the gas is hotter, with the smallest ones gaining the most speed after bumping into heavy molecules. In the upper atmosphere solar ultraviolet radiation continually breaks up (dissociates) molecules. Hydrogen, the lightest atom, moves the fastest, and sometimes, before it recombines with another atom or molecule, it shoots out into space, escaping the planet's gravity. In this way, a planet loses water, as the oxygen left behind combines with other elements.

How much water did young Venus have? We know that pretty well, based on Pioneer Venus measurements of the amount of the hydrogen isotope deuterium, sometimes called 'heavy hydrogen.' A normal hydrogen atom has only a proton in its nucleus, but deuterium has a proton and a neutron. So deuterium is about twice as heavy as normal hydrogen. Deuterium cannot escape to space as easily as normal hydrogen, because deuterium is heavier.

Pioneer Venus found that the deuterium amount on Venus was about 1 percent of the hydrogen still in the atmosphere. That is a big enrichment over the initial deuterium on Venus, which was believed to be only 50 parts per million (which is 0.005%) of total hydrogen. Based on these data, Mike McElroy and colleagues[7] concluded that Venus initially had enough water to form a layer 8 meters thick, if it covered the entire planet. This was a lower limit, because some deuterium also must have escaped.

Moreover, the later Galileo mission to Jupiter found that the deuterium proportion of hydrogen on Jupiter was only 25 ppm, not 50 ppm. Jupiter's gravitational field is too strong to allow even normal hydrogen to escape, so 25 ppm is a better estimate of primordial deuterium abundance in the solar nebulae from which the planets formed. Therefore McElroy's estimate of the initial water on Venus should be increased to at least 16 meters.

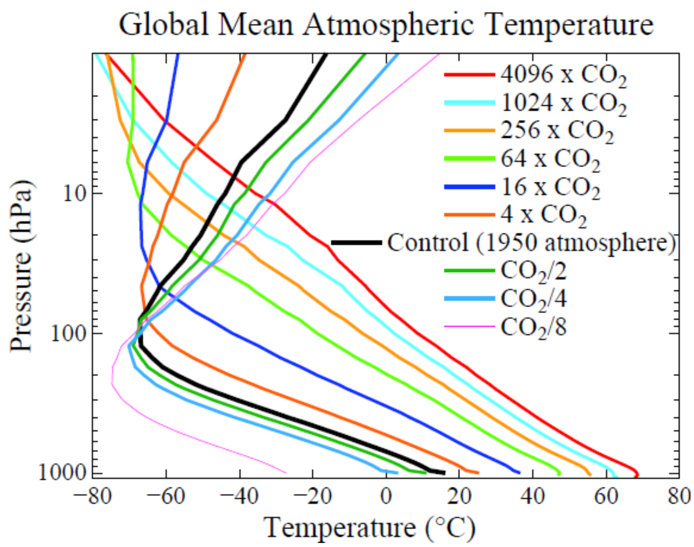

Fig. 10.2. Global mean temperature profile for successive doublings of atmospheric CO_2.

Sixteen meters of water is only about half of 1 percent of the amount of water on Earth today, but it is still a lot of water to be lost via hydrogen escape. That much water could not have escaped if the Venus atmosphere had a "cold trap" like the one on Earth. The upper troposphere on Earth, at a height of about 10 miles, is so cold that it 'wrings out' almost all the water. When air mixes upward from Earth's lower atmosphere it must pass through this cold trap. The upwelling air then becomes so dry that it delivers very little water to the outer fringes of the atmosphere. Water cannot escape from Earth today, at least not a significant amount of water.

Yet Venus' ocean escaped, we know from its deuterium amount. How could that be, when a cold trap was expected to exist on Venus?[8,9] Andy Ingersoll[10] suggested a solution to this conundrum: a runaway greenhouse. He argued that, if a planet were warm enough for water to be a major constituent of the atmosphere, the greenhouse effect would force continuous evaporation of surface water, and convection would carry water vapor to great altitude, leading to more water being available for dissociation by ultraviolet light in the upper atmosphere.

In effect, Ingersoll said: if the climate forcing is large enough, so the atmospheric temperature is high enough, so the water vapor mixing ratio is large enough, the resulting blocking of infrared heat transport will force a pumping of water vapor into the upper atmosphere, where the hydrogen can escape. Sounds like a Rube Goldberg machine?

No, it is a simple concept, but it must be tested with realistic calculations. Ingersoll assumed that water vapor absorbs at all wavelengths, but actually there are 'windows,' some spectral regions in which the gas is transparent. Also, we should calculate the upward transport of water vapor via a realistic description of moist convection in a global climate model.

Such calculations,[11] shown in Figure 10.2, confirm the essence of Ingersoll's thesis. To explain this figure, it helps to first define the concept of a climate forcing. We will need the climate forcing concept later to interpret climate change on Earth.

A climate forcing is an imposed perturbation of a planet's energy balance. It is measured in watts per square meter (W/m^2) averaged over the planet. Let's consider a forcing of +4 W/m^2, which is the climate forcing caused by doubling the amount of CO_2 in the air. The same magnitude of forcing occurs if the brightness of the Sun increases by about 2 percent.[12] In either case, the response to this forcing – this imposed planetary energy imbalance – will be a warming of the planet until energy balance with space is restored.

The climate forcing due to any CO_2 change can be calculated accurately because the absorption by CO_2 is accurately known at all wavelengths. A forcing of approximately 4 W/m^2 continues to occur for each CO_2 doubling over a remarkably large range of CO_2. Additional CO_2 continues to be effective even when CO_2 absorption bands are saturated at Earth's surface, because absorption is not saturated higher in the atmosphere. Added CO_2 still causes thermal emission to space to occur from higher, colder levels, reducing heat emission to space, thus causing a planetary energy imbalance and a global warming to restore energy balance.

The heavy black curve in Figure 10.2 is the temperature profile produced by the climate model for contemporary atmospheric CO_2 amount. Note the minimum at pressure level about 100 mb; that minimum is the 'cold trap.' The other curves show the temperature profile after the CO_2 amount is repeatedly doubled (or halved). After six doublings, to a CO_2 amount 64 times greater than the contemporary amount, the cold trap is eliminated. For still larger CO_2 amounts, the temperature at altitude continues to rise, allowing even more water vapor to be pumped to the upper atmosphere, where hydrogen can escape to space.

Such large CO_2 amounts cannot be achieved by burning fossil fuels, because the weathering process extracts atmospheric CO_2 and deposits it as limestone on the ocean floor. On the other hand, atmospheric temperature high enough to drive hydrogen escape can be achieved by moving closer to the Sun or by waiting for the Sun to become more luminous.

Consider the case of 10 CO_2 doublings, i.e., a CO_2 increase by a factor of 1024. Ten doublings yields a climate forcing of about 40 W/m^2, which produces a temperature profile that would carry water vapor to the upper reaches of the atmosphere. Compare that 40 W/m^2 forcing to the climate forcing that occurs if we move an Earth-like planet, that is, a planet with an ocean, from Earth's orbit to the orbit of Venus. Solar irradiance at that distance from the Sun is twice as great as at Earth. Solar heating of Earth, if moved to the Venus orbit, would increase from 240 to 480 W/m^2, thus causing a climate forcing of 240 W/m^2 relative to the climate on Earth today.

When Venus had an ocean, Venus must have been more Earth-like than today, with water clouds, but with no stratospheric cold trap. Water vapor would be pumped efficiently to the upper atmosphere, where hydrogen could escape to space. The modest ocean on Venus was lost to space quickly, probably within hundreds of millions of years or less. Once the ocean was gone, the CO_2 belching from volcanoes stayed in the atmosphere and Venus was on its way to being a baked-crust permanent hothouse.

Will Earth have a runaway, baked-crust greenhouse? Yes, it will, but not soon. Today nuclear fusion in the Sun's core is converting hydrogen to helium, with the release of energy that provides the Sun's luminosity. The luminosity is increasing now at a rate of about 10 percent per billion years.[13] As the Sun, an ordinary 'main sequence' star, exhausts the hydrogen in the core, nuclear reactions will continue, first with hydrogen fusion in the Sun's outer layers and then via fusion of helium into larger elements in the Sun's core.

Eventually the Sun will expand into its Red Giant phase, engulfing Earth about 5 billion years in the future. Before then, perhaps as soon as one billion years from now, Earth will lose its ocean and experience a runaway, baked crust greenhouse. However, a billion years is far enough in the future that you do not need to worry about it. Before then, humanity, if it does not do itself in sooner, should have the capability to emigrate to a more hospitable place.

There is the possibility of a milder runaway greenhouse effect on time scales that today's young people should be concerned about. I will call this milder runaway greenhouse the 'existential threat' or ET runaway greenhouse.

The ET runaway greenhouse is a possible future for humanity, if we should be so foolish to continue much longer to ignore the climate threat posed by burning most of the fossil fuels. In the ET runaway greenhouse scenario, we allow high fossil fuel emissions to continue to the point that rapid disintegration of the Antarctic and Greenland ice sheets begins, causing rapid increase of sea level of many meters and the loss of all coastal cities.

Loss of coastal cities would occur at the same time that low latitudes are becoming unreasonably hot and humid. Global emigration pressures could become so great that global governance breaks down. Chaos for humanity would ensue. That is the ET runaway greenhouse.

Let me be clear: I am optimistic that we will be able to avoid the ET runaway greenhouse. I believe that the United States and China will realize that we are all in the same boat, that we need to cooperate. We can, together, use our technological prowess to pull back from the brink.

Pulling back from the brink will not happen without effort. It is not enough to demand that governments address the global climate change matter. None of the political parties are advocating an approach that would actually work. It is necessary that the public, especially young people, understand the actions that are needed. That is my purpose in writing this book.

What was the error in *Storms of My Grandchildren*? In that book, extraterrestrial visitors to Earth in 2525 find a lifeless planet. Such an outcome is conceivable, given the potential chaos accompanying an ET runaway greenhouse. The flaw in *Storms* is that the visitors witnessed boiling tropical oceans. That physical state in not possible on a 500-year time scale. That sentence should be eliminated or altered.

Planetary science became my passion in the first half of the 1970s. My interest in becoming an astronaut waned. I spoke with Brian O'Leary, who applied, successfully, to the astronaut selection process in 1967. That was precisely the class that I, at the last moment, decided not to apply for. Brian resigned one year after being accepted into the astronaut program. His primary reason for giving up his astronaut ambition was realization that it was not practical to be an astronaut and at the same time be a fulltime, competitive scientist.

I was still early in my career path aimed at becoming a scientist, and I still needed to catch up. Someone such as Jim Pollack had a broader understanding than I had. I thought that I would soon be caught up, and Anniek and I could start living like normal people, and she believed me.

I did not foresee the emergence of more riveting issues, that would emerge in steps, one, two, three, the first step a seemingly innocuous involvement in weather prediction.

[1] Irradiance is the flux of radiant energy per unit area normal to the direction of radiation flow.
[2] The law says energy radiated from a surface is proportional to the 4th power of its absolute temperature, with temperature measured in degrees Kelvin (Kelvin temperature in degrees is Celsius temperature plus 273).
[3] Tyndall, J., Radiant Heat, Longmans, Green, and Co., London, 1872 (available: https://archive.org/stream/contributionsto01tyndgoog#page/n441/mode/1up).
[4] Their triatomic structure results in vibrational energy states that are excited by infrared photons.
[5] Pollack, J.B., Toon, O.B. and Boese, R., Greenhouse models of Venus' high surface temperature, as constrained by Pioneer Venus measurements, J. Geophys. Res., 85, A13, 8223-8231, 1980.
[6] Beerling, D.J., J.R. Leake, S.P. Long, J.D. Scholes, J. Ton, P.N. Nelson, M. Bird, E. Kantzas, L.L. Taylor, B. Sarkar, M. Kelland, E. DeLucia, I. Kantola, C. Muller, G.H. Rau and J. Hansen, 2018: Farming with crops and rocks to address global climate, food and soil security, *Nature Plants*, **4**, 138-147, doi: 10.1038/s41477-018-0108-y.
[7] McElroy, M.B., M.J. Prather and J. Rodriquez, Escape of hydrogen from Venus, Science 215, 1614-1615, 1982.
[8] Sagan, C., The radiation balance of Venus, Cal Tech JPL Tech. Rept. 32-34, 23 pp., 1960.
[9] Gold, T., Outgassing processes on the moon and Venus, in The Origin and Evolution of Atmospheres and Oceans, Eds. Brancazio & Cameron, New York, Wiley, 249-256, 1964.
[10] Ingersoll, A.P., The runaway greenhouse: a history of water on Venus, J. Atmos. Sci., 26, 1191-1198, 1969.
[11] Hansen, J., M. Sato, G. Russell and P. Kharecha, Climate sensitivity, sea level and atmospheric carbon dioxide, *Phil. Trans. Roy. Soc. A.* **371**, 20120294, 2013; see Figure 7.
[12] Solar irradiance at Earth averaged over the year is about 1370 W/m^2 , but this is reduced by a factor of four when averaged over Earth's surface area, and only about 70 percent of the incident radiation is absorbed.
[13] Sackmann, I.J., A. Boothroyd, and K. Kraemer, Our sun III: present and future, *Astrophys. J.* **418**, 457-468, 1993.