Physical Modeling of Earth's Climate

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IT IS A GREAT HONOR to be chosen by the Royal Swedish Academy of Sciences to receive the Nobel Prize established through the generosity and foresight of Mr. Nobel. It is likewise a great pleasure to give a talk on global warming, the subject that I have enjoyed exploring throughout my career.

Figure 1. The Blue Marble.

Figure 2. This 1969 photograph shows AOS Senior Scientists Kirk Bryan (left) and Suki Manabe talking with GFDL Director Joseph Smagorinsky, who brought GFDL to Princeton because of the intellectual environment and resources available here. Photo courtesy of the Geophysical Fluid Dynamics Laboratory.

On this occasion, I would like thank the late Joseph Smagorinsky, the inaugural director of the Geophysical Fluid Dynamics Laboratory of the U.S. National Oceanic and Atmospheric Administration. It has been a great privilege and pleasure to work at the Laboratory, unraveling the secrets of climate change.

Today, I would like to discuss the role of greenhouse gases in climate change, using relatively simple climate models that we constructed prior to 1990. I begin with an explanation of the so-called greenhouse effect in the atmosphere.

THE GREENHOUSE EFFECT OF THE ATMOSPHERE

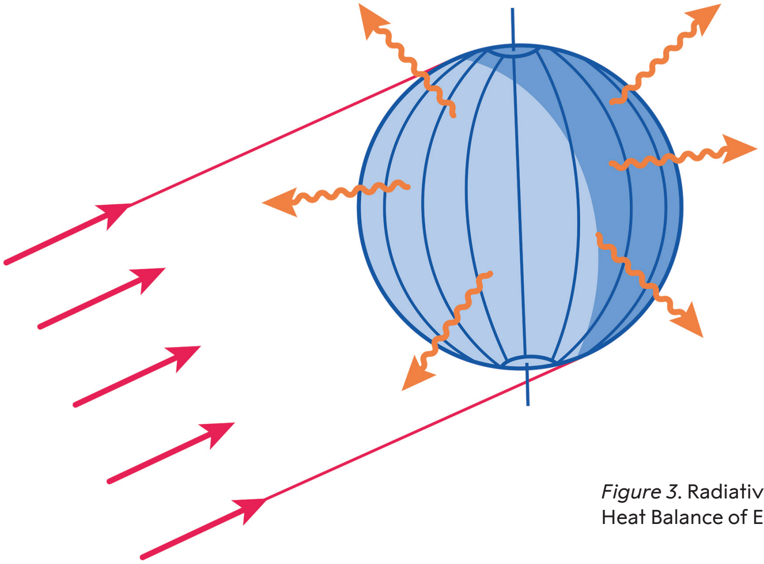


Figure 3. Radiative Heat Balance of Earth.

The energy balance of our planet is maintained between net incoming solar shortwave radiation and outgoing longwave radiation at the top of the atmosphere. According to satellite observation, the globally averaged value of outgoing longwave radiation is ~240 Wm−2. Assuming that the Earth-atmosphere system radiates as a blackbody according to the Stefan-Boltzmann law of blackbody radiation, one can estimate the effective emission temperature of the planet.

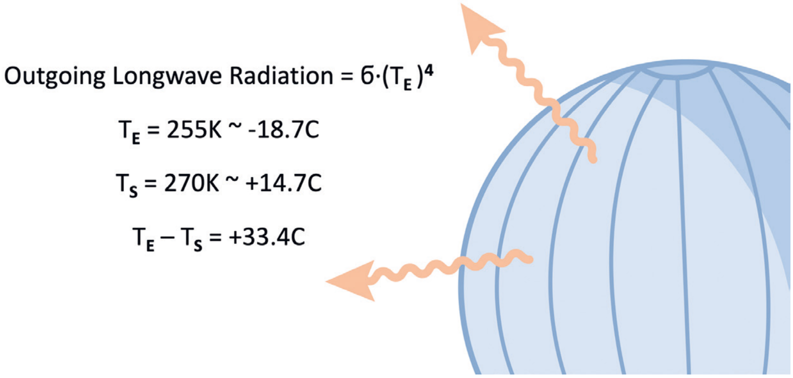


Figure 4. Temperature of Planetary Emission.

Temperature thus obtained is –18.7C, which is colder than +14.7C, the global mean temperature of the Earth's surface. This implies that the Earth's surface is warmer than it would be in the absence of the atmosphere by as much as 33C. In other words, the atmosphere has so-called greenhouse effect that increases the temperature of the Earth's surface by as much as 33C. It is the satellite observation of outgoing longwave radiation that has provided the most convincing evidence for the existence of the greenhouse effect of the atmosphere.

The figureon next page was designed to illustrate schematically the thermal structure and the greenhouse effect of the atmosphere. The slanted line indicates schematically the idealized, vertical temperature profile of the troposphere, where temperature decreases almost linearly with height. The vertical line segment above the slanted line illustrates schematically the almost isothermal lower stratosphere. The dot in the middle troposphere indicates the effective emission center of the outgoing radiation from the top of the atmosphere. Its temperature is –18.7C, which may be compared with +14.7C, the global mean temperature of the Earth's surface. The latter is warmer than the former by about 33C, indicating the magnitude of the greenhouse effect of the atmosphere.

Radiative transfer from the Earth's surface and in the atmosphere obeys Kirkhoff's law. It requires that, for a given wavelength, the

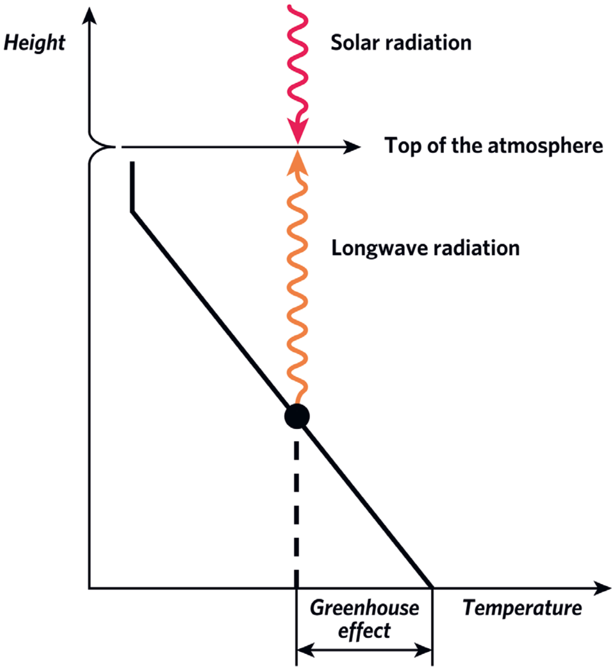


Figure 5. Greenhouse Effect of the Atmosphere.

absorptivity of a substance is equal to its emissivity, which is defined as the ratio of the actual emission to the theoretical emission from a blackbody. Because Earth's surface behaves almost as a blackbody, it has an absorptivity that is close to one, absorbing almost completely the downward flux of longwave and shortwave radiation that reaches it. In keeping with Kirkhoff's law, the Earth's surface emits an upward flux of longwave radiation almost as a blackbody would. As this upward flux penetrates into the atmosphere, it is depleted due to the absorption by greenhouse gases such as water vapor, carbon dioxide, nitrous oxide, and methane, but it is also accreted because of the emission from these gases. In short, the upward flux decreases or increases with height, depending on whether the depletion is larger than accretion or vice versa.

Although these greenhouse gases are minor constituents of the atmosphere, as a whole they absorb a major fraction of the upward flux of blackbody radiation emitted by the Earth's surface. On the other hand, the atmosphere also emits the upward flux of longwave radiation. Since Kirkhoff's law requires the absorptivity of the atmosphere to be equal to its emissivity, the absorption of the upward flux emitted by the relatively warm Earth's surface is substantially larger than the emission of the upward flux by the relatively cold atmosphere. Thus, the atmosphere traps a substantial fraction of the upward flux of longwave radiation emitted by the Earth's surface before it reaches the top of the atmosphere, thereby keeping the Earth's surface warm and habitable.

MECHANISM OF GLOBAL WARMING

So far, I have explained why the atmosphere has a so-called greenhouse effect that traps a substantial fraction of the upward flux of longwave radiation emitted by the Earth's surface. Now I shall explain why temperature increases not only at the Earth's surface but also in the troposphere as the concentration of a greenhouse gas increases in the atmosphere.

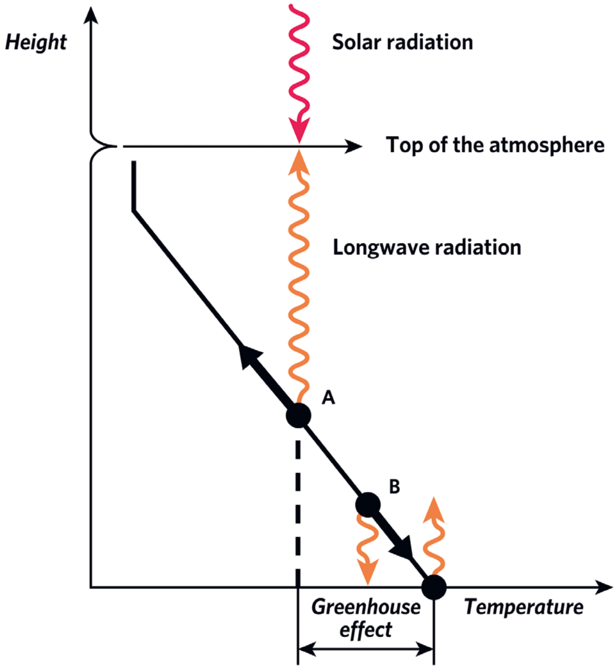


Figure 6. Mechanism of Global Warming.

If a greenhouse gas such as carbon dioxide increases in the atmosphere, the infrared opacity of air increases, making it harder for the radiation emitted from the lower layer to reach the top of the atmosphere. Consequently, the average height of the layer, from which the outgoing longwave radiation originates, increases as the concentration of greenhouse gas increases in the atmosphere. In short, the more opaque the atmosphere is, the higher is the effective center of the upward flux that reaches the top of the atmosphere. Since the effective center (A) of the outgoing radiation is located in the troposphere, where temperature decreases with increasing height, the temperature of the center decreases as it moves upward, thereby reducing the outgoing radiation from the top of the atmosphere.

The change in the concentration of greenhouse gas affects not only the outgoing longwave radiation from the top of the atmosphere but also the downward flux that reaches the Earth's surface. If the concentration of greenhouse gas increases in the atmosphere, the infrared opacity of air increases, making it harder for the radiation from the higher layer of the atmosphere to reach the Earth's surface. Consequently, there is a downward shift of the effective center (B) of the downward flux, as the concentration of greenhouse gas increases in the atmosphere. In short, the more opaque the atmosphere is, the lower is the emission center of the downward flux that reaches the Earth's surface. Because temperature increases with decreasing height in the troposphere, the temperature at the center also increases as it moves downward, thereby increasing the downward flux that reaches the Earth's surface.

The radiative response of the surface-troposphere system to an increase in greenhouse gas can be regarded as the net result of two related processes. The first process involves the increase in the downward flux of longwave radiation that increases the temperature of the Earth's surface. Over a sufficiently long period of time, the Earth's surface returns to the overlying troposphere practically all the radiative energy it receives, with thermal energy being transferred upward through moist and dry convection, longwave radiation, and large-scale circulation in the atmosphere. Thus, temperature increases not only at the Earth's surface but also in the overlying troposphere.

The second process involves the upward flux of longwave radiation at the top of the atmosphere in response to an increase in atmospheric concentration of greenhouse gas. If the amount of greenhouse gas were to increase without allowing the temperature of the surface–troposphere system to change, the upward flux of longwave radiation at the top of the atmosphere would decrease, as explained earlier. To maintain the radiative heat balance of the planet as a whole, the surface-troposphere system warms just enough for the effect of these two processes to balance, such that the top-of-atmosphere flux of outgoing radiation remains unchanged despite the warming. The global scale increase of the overall temperature of the surface-troposphere system is often called global warming.

An important factor that affects the magnitude of global warming is the positive feedback process that involves water vapor, which absorbs and emits strongly over much of the spectral range of terrestrial longwave radiation and is mainly responsible for the powerful greenhouse effect of the atmosphere. As we know, the absolute humidity of air usually increases with increasing temperature, thereby increasing the greenhouse effect of the atmosphere. The positive feedback effect between temperature and the greenhouse effect of the atmosphere is called ‘water vapor feedback’. It magnifies the global warming that is induced by long-lived greenhouse gases such as carbon dioxide.

RADIATIVE CONVECTIVE EQUILIBRIUM

In the mid-1960s we developed a one-dimensional, vertical column model of the atmosphere, in which heat balance in the atmosphere and the Earth’s surface are maintained through close interaction between radiative and convective heat transfer. The model tuned out to be very useful for evaluating how temperature changes at the Earth’s surface and in the atmosphere in response to the change in the atmospheric concentration of carbon dioxide.

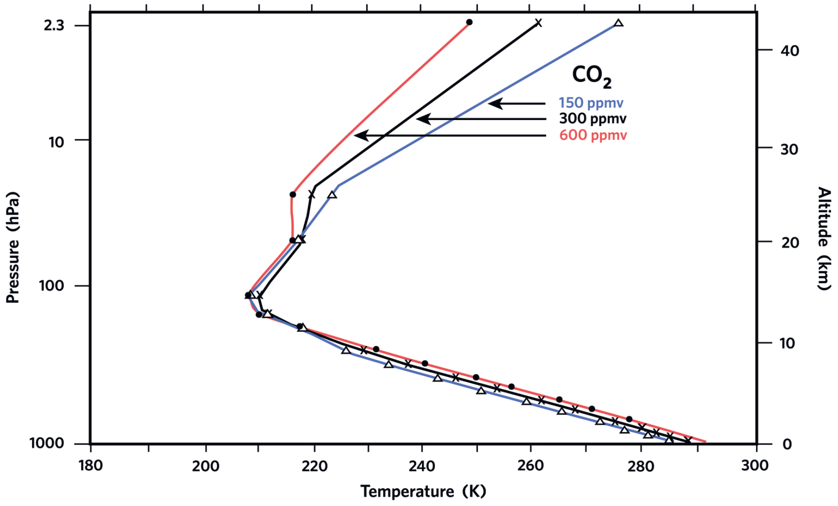


Figure 7. Radiative-Convective Equilibrium. Manabe & Wetherald, 1967.

Using this model, we obtained the vertical temperature profile of the atmosphere in radiative-convective equilibrium not only for the normal concentration of the atmosphere, 300 ppm by volume, but also for two other concentrations, 150 ppm and 600 ppm. The above figure shows vertical temperature profiles of the coupled atmosphere-earth surface system, in radiative-convective equilibrium, which are obtained for these three concentrations. As explained already, the temperature increases not only at the Earth’s surface but also in the troposphere as the atmospheric concentration of carbon dioxide doubles from 150 to 300 ppm and 300 to 600 ppm, whereas it decreases in the stratosphere.

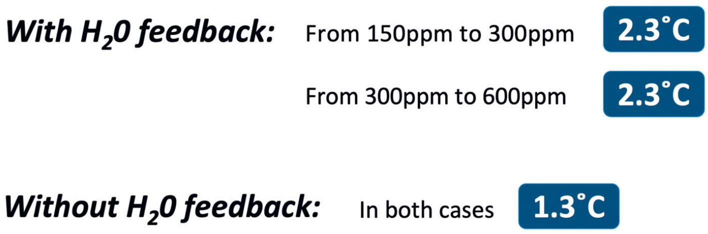


Figure 8. Surface Temperature Change due to CO2 doubling.

The magnitude of the warming in the troposphere is 2.3C in both cases and is practically identical in both cases.

To evaluate quantitatively the influence of the water vapor feedback upon the simulated warming, we conducted another set of runs in which the water vapor feedback was disabled. In these runs, the distribution of absolute humidity was prescribed to remain unchanged rather than being adjusted to maintain a constant relative humidity. From the difference among the three states of radiative-convective equilibrium thus obtained, we estimated the magnitude of the equilibrium response of surface temperature in the absence of water vapor feedback. We found that surface temperature increases by approximately 1.3C in response to the doubling of atmospheric carbon dioxide. It is much smaller than 2.3C that we got in the presence of the water vapor feedback. These experiments indicate that water vapor has a powerful feedback effect that magnifies surface temperature change by a substantial factor.

COUPLED ATMOSPHERE-OCEAN-LAND MODEL

The one-dimensional, radiative-convective model was developed as an important step towards the development of the three-dimensional, general circulation model of the atmosphere, which in turn evolved into a coupled atmosphere-ocean model.

In the box diagram shown here, the coupled model consists of three major components, which are the general circulation model of the atmosphere, that of the ocean, and a simple, heat and water balance model of the continental surface. Although the initial version of the coupled model was constructed in the late 1960s, it took two more decades before the coupled model with realistic geography became ready for the global warming experiment conducted in the late 1980s. The result from the experiment was published in the late 1980s and was discussed extensively in the first report of the Inter-Governmental Panel on Climate Change published in 1990. For further details of this study, see our book Beyond Global Warming, recently published by Princeton University Press.

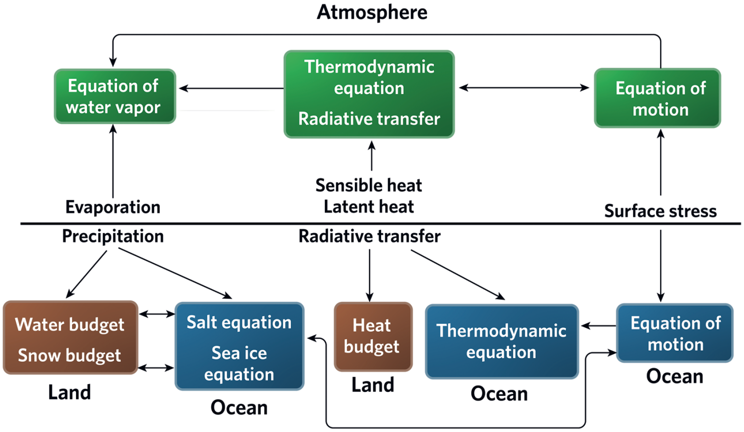


Figure 9. Coupled Ocean-Atmosphere-Land Model. Manabe & Bryan, 1969.

CHANGE IN WATER AVAILABILITY

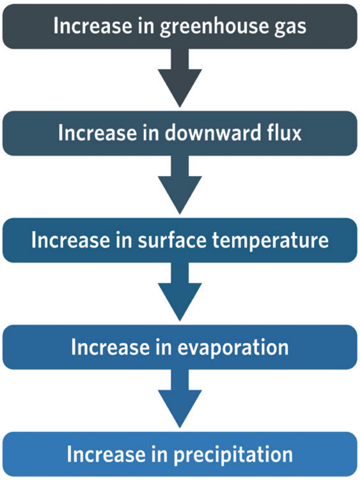
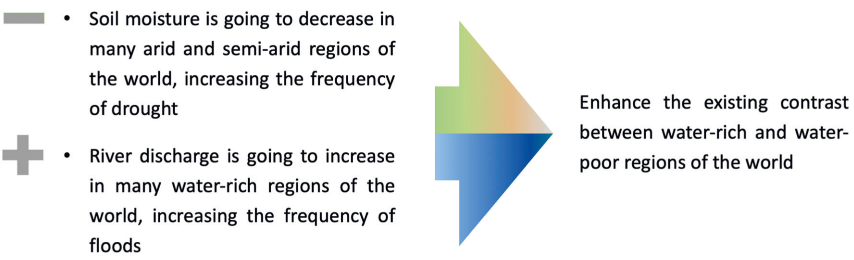


Figure 10. Acceleration of Hydrologic Cycle.

Global warming involves changes not only in temperature but also in the rate of evaporation and that of precipitation. If a greenhouse gas such as water vapor or carbon dioxide increases in the atmosphere, the downward flux of longwave radiation increases at the Earth's surface as explained already, thereby increasing the temperature of the Earth's surface. Since the saturation vapor pressure at a wet surface (e.g., ocean) increases with rising surface temperature, it is expected that the rate of evaporation from the Earth's surface also increases, so long as the relative humidity of the overlying atmosphere does not change systematically. Given sufficient time, a global-scale increase in the rate of evaporation results in a corresponding increase in the rate of precipitation, thereby increasing the strength of the global water cycle.

Global warming involves not only the global mean rates of precipitation and evaporation but also their geographical distributions, due mainly to the increase in the rate of horizontal transport of water vapor by large-scale circulation in the atmosphere. When temperature increases in the atmosphere in response to the increase in the concentration of long-lived greenhouse gas such as carbon dioxide, it is expected that the absolute humidity of air increases, keeping the relative humidity of air unchanged through precipitation. Thus, it is expected that horizontal transport of water vapor by large scale circulation also increases in the atmosphere. This is the main reason why the distribution of precipitation changes differently from that of evaporation as global warming proceeds, affecting substantially the distribution of water availability such as the rate of river discharge and the amount of soil moisture at the continental surface.



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- Soil moisture is going to decrease in many arid and semi-arid regions of the world, increasing the frequency of drought

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- River discharge is going to increase in many water-rich regions of the world, increasing the frequency of floods

Enhance the existing contrast between water-rich and water-poor regions of the world

Figure 11. Changes in Water Availability and Its Implication.

For example, precipitation usually increases in many water-rich regions in high northern latitudes and heavily precipitating regions of the tropics, increasing river discharge and frequency of floods. In contrast, soil moisture usually decreases in many relatively arid regions in the subtropics and other water-poor regions that are relatively dry, increasing the frequency of drought.

Figure 12. Changes in Water Availability and Its Implication.

The implied amplification of existing difference in water availability between water-poor and water-rich regions presents a very serious challenge to the water-resources managers of the world.

Thank you very much.