PART V

SPECIAL TOPICS

18

Climate Dynamics

Summary: This chapter briefly reviews the principal factors controlling the climate on our planet and provides an introduction to the greenhouse effect. We first summarize the global heat budget and then describe the major convective cells and review the major wind systems. The chapter ends with a note on the role of the ocean in maintaining our climate and a brief discussion of a possible global warming.

18-1 CLIMATE VERSUS WEATHER

Climate is to be distinguished from *weather*. Whereas *weather* includes the detailed behavior of the atmosphere on a time scale of a day to a week, *climate* represents the prevailing or average weather conditions over a period of years. In other words, the climate of the earth can be regarded as the basic state of the atmosphere, subject to variations over years, centuries, millennia, and beyond, but the weather corresponds to its incessant and short-lived instabilities. The engine of climate is a global convection carrying heat from the warmer tropical belt to the much colder polar regions, and its primary manifestation is the distribution of prevailing winds over the globe.

18-2 GLOBAL HEAT BUDGET

Because the long-term gradual cooling of the earth's core contributes insignificantly to the heat input near the surface, the incoming solar radiation can be considered as the sole source of heat. From its hot surface ($T \simeq$ 5750 K), the sun emits most of its energy in short wavelengths (200 to 4000 nm; 1 nm = 10^{-9} m), of which about 40% is in the visible range (400 to 670 nm). According to the Stefan–Boltzmann law, a so-called blackbody (a perfect emitter and absorber of radiation) emits a radiative flux depending on its temperature

$$F = \sigma T^4, \tag{18-1}$$

where σ is a constant equal to 5.67 10^{-8} W/m$^2 \cdot$K^4 and T is the absolute temperature. Idealizing the sun to a blackbody, we obtain $F_{sun} = 6.2 \times 10^7$ W/m^2 as the outgoing energy flux from the sun's surface. Given the size of the sun, the sun–earth distance, and the earth's area exposed to the sun, the earth receives only a minute fraction of the sun's output: 1380 W/m^2. Averaged over the entire earth's surface (equal to four times the projected area facing the sun), this incident flux amounts to $I = 344$ W/m^2.

Let us at this point first discard the thickness of the atmosphere and idealize the earth's land and sea surface plus atmosphere as a thin sheet insulated from below. Of the incident radiation, a fraction is reflected out to space by snow, ice, mostly clouds, and everything else that is bright. With α as the reflection coefficient, called the *albedo* ($\alpha \simeq 0.34$), the amount of radiation reflected is $R = \alpha I = 117$ W/m^2. The difference is the amount absorbed by the earth's surface: $A = I - R = (1 - \alpha)I = 227$ W/m^2 (Figure 18-1). Because the earth is in overall thermal equilibrium (its temperature is not constantly rising), its outgoing radiation matches absorption, and the earth emits a

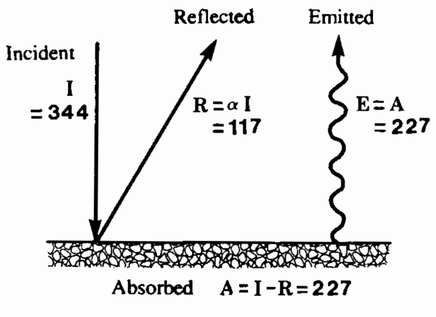


Figure 18-1 Simplest possible model of the earth's heat budget. Straight lines indicate shortwave radiation whereas the wavy line represents longwave radiation. (Flux values are in watts per square meter.) Under this scenario, which does not account for the atmosphere, the earth's average temperature would be a freezing −21°C.

radiative flux E equal to A. This outgoing radiation is in the form of longer wavelengths than the incoming solar radiation and is termed longwave radiation. Assuming as for the sun that the earth behaves as a blackbody and using the preceding values, we state

$$\sigma T^4 = E = 227 \text{ W/m}^2,$$

and deduce a mean temperature for the earth to be $T = 251$ K = −21°C. This value is obviously much below the average temperature of the earth as we know it (about 15°C).

The failure of this simple model resides in the neglect of the atmospheric layer. The preceding value is more representative of the temperature at the top of the atmosphere than at ground level.

As a next step, we distinguish the atmosphere from the earth's surface (Figure 18-2). The incident shortwave radiation from the sun is unchanged ($I = 344$ W/m^2); of it, the fraction α_1 (= 0.33) is reflected back to space, primarily by clouds and

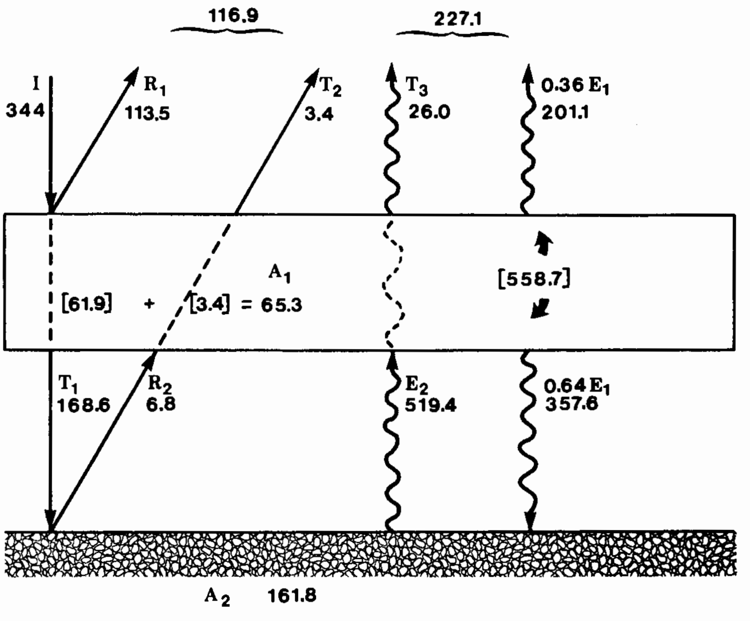


Figure 18-2 A second model of the earth's heat budget, which distinguishes the atmospheric layer from the earth's surface. All flux values are in watts per square meter. Under this scenario, the earth's average temperature would be a very warm 36°C. Here the greenhouse effect (flux loop between the earth's surface and the atmosphere) is present and exaggerated. Note how this effect causes the longwave radiative fluxes from the earth and atmosphere to exceed the incident shortwave radiative flux from the sun.

secondarily by particulate matter ($R_1 = \alpha_1 I = 113.5$ W/m^2), the fraction β_1 ($= 0.49$) is transmitted to the earth's surface ($T_1 = \beta_1 I = 168.6$ W/m^2), and the rest is absorbed by the atmosphere. The earth's surface (snow, ice, etc.) reflects a fraction α_2 ($= 0.04$) of what it receives ($R_2 = \alpha_2 T_1 = 6.8$ W/m^2) and absorbs the rest ($A_2 = T_1 - R_2 = 161.8$ W/m^2). Of the portion R_2 reflected from the earth's surface, the fraction β_1 is transmitted through the atmosphere and out to space ($T_2 = \beta_1 R_2 = 3.4$ W/m^2), whereas the rest is absorbed by the atmosphere. Thus the atmosphere absorbs shortwave radiation directly from the sun ($I - R_1 - T_1$) and indirectly from the earth below ($R_2 - T_2$), and the net is

$$A_1 = (I - R_1 - T_1) + (R_2 - T_2)$$
$$= [1 - \alpha_1 - \beta_1 + \beta_1\alpha_2(1 - \beta_1)]I$$
$$= 65.3 \text{ W/m}^2 .$$

Then both the atmosphere and the earth's surface emit longwave radiation, in amounts equal to their total intakes of both shortwave and longwave radiation. If the atmosphere emits a flux E_1, some of it goes upward into space and the rest goes downward to the earth. Because the top of the atmosphere, where the outgoing radiation originates, is colder than its lower layers, where the earthbound radiation originates, the two amounts are not equal; a representative split is 36% to space and 64% to the earth. Thus, the earth receives $0.64E_1$ of longwave radiation from the atmosphere in addition to the amount A_2 received in short waves, and its emission E_2 must equal their sum:

$$E_2 = A_2 + 0.64\ E_1 . \tag{18-2}$$

At this point, we still do not know either E_1 and E_2, but we can already conclude that the presence of atmospheric radiation toward the earth's surface establishes a loop, whereby the earth's surface emits some radiation, a portion of which returns to the earth. As a consequence, the earth's surface must emit more radiation in the presence of an atmosphere than in its absence and (according to the Stefan–Boltzmann law) must be correspondingly warmer. This is the *greenhouse effect*, so called because of its similarity to the trapping of longwave infrared radiation by the glass panes of a greenhouse.

Of the amount E_2 radiated by the earth's surface and entering the atmosphere, a fraction β_2 ($= 0.05$) is transmitted and lost to space ($T_3 = \beta_2 E_2$), with the remainder being absorbed by the atmosphere ($E_2 - T_3$).

If the atmosphere absorbs the amounts A_1 and $E_2 - T_3$ in shortwave and longwave radiations respectively, its total emission must be equal to their sum; that is,

$$E_1 = A_1 + E_2 - T_3$$
$$= A_1 + (1 - \beta_2)E_2 . \tag{18-3}$$

From (18-2) and (18-3), we can derive the emission fluxes E_1 and E_2 to find $E_1 = 558.7 \text{ W/m}^2$ and $E_2 = 519.4 \text{ W/m}^2$. (Note that both are higher than the incident flux $I = 344 \text{ W/m}^2$.) Then, using the Stefan–Boltzmann law (18-1), we estimate the mean temperature of the earth's surface to be $T = (519.4/\sigma)^{1/4} = 309 \text{ K} = 36°\text{C}$. This temperature is higher than the first estimate, thanks to the capping effect of the atmosphere (greenhouse effect) but is unrealistically high.

In reality, the warming influence of the greenhouse effect is partially short-circuited by the hydrological cycle. As water evaporates over the ocean and land, latent heat is extracted from the earth's surface. (Latent heat is the heat required to change the phase of a substance, here to transform liquid water into water vapor. The latent heat of water is 4000 J/kg.) This water vapor rises through the atmosphere, where it condenses in clouds before returning to the earth's surface as rain (liquid phase). Thus, the latent heat extracted from the earth's surface is released in the atmosphere, causing a net heat flux from the earth to the atmosphere that is not in the form of radiation. To this latent-heat flux is added a convective heat transfer. With an estimated total nonradiative heat flux $Q = 113.6$ W/m^2, the earth and atmospheric balances, (18-2) and (18-3), must be amended as (Figure 18-3)

$$E_2 = A_2 + 0.64\ E_1 - Q, \tag{18-4}$$

$$E_1 = A_1 + E_2 - T_3 + Q, \tag{18-5}$$

yielding $E_1 = 573.2$ W/m^2 and $E_2 = 415.0$ W/m^2. From the radiation law, we deduce a corrected estimate of the mean temperature at the earth's surface: $T = (415.0/\sigma)^{1/4} = 292$ K = 19°C. This third estimate is in good agreement with the seasonally and globally averaged temperature on the earth's surface. All in all, we conclude that the greenhouse effect due to the presence of the atmosphere (especially with regard to its near opacity to longwave radiation) raises the temperature of the earth's surface and that the impact of this effect is partially canceled by the hydrological cycle.

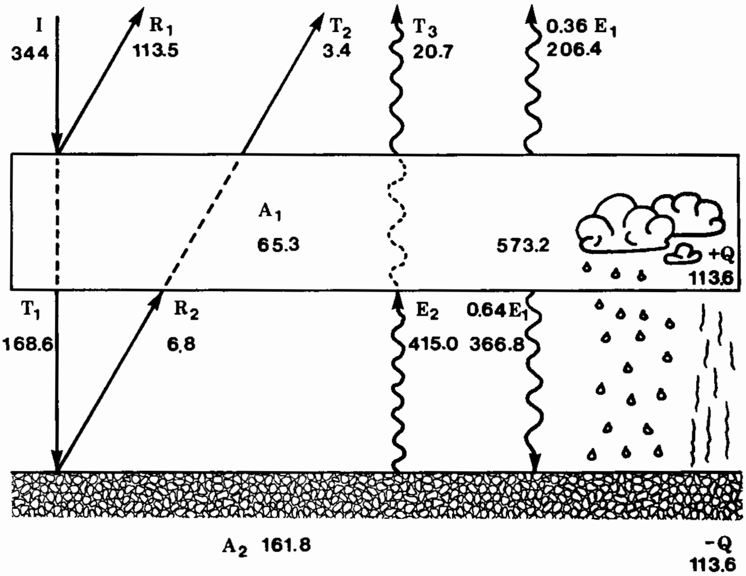


Figure 18-3 A third model of the earth's budget, with atmosphere and hydrological cycle. All flux values are in watts per square meter. This scenario includes the greenhouse effect tempered by the hydrological cycle, resulting in a realistic mean temperature at the earth's surface of 19°C.

18-3 GENERAL ATMOSPHERIC CIRCULATION

The preceding considerations exposed the globally averaged heat budget, glossing over all spatial variations. However, that the tropical regions of the globe receive a disproportionate amount of solar radiation, because of their better exposure, is not to be overlooked. Although the earth receives considerably more heat at low latitudes than near the poles, its outgoing radiation is more uniformly spread, decreasing only slightly with latitude (Figure 18-4). The resulting heat excess at low latitudes and deficit at high latitudes call for a poleward heat transfer. George Hadley, an eighteenth-century Englishman, hypothesized that this transfer is accomplished by a giant thermally driven circulation: Warm tropical air rises and flows toward each pole, where it cools and sinks, returning to the tropics along the surface (Hadley, 1735). As it turns out, Hadley was partly correct, insofar as such convective circulations exist on both sides of the equator,

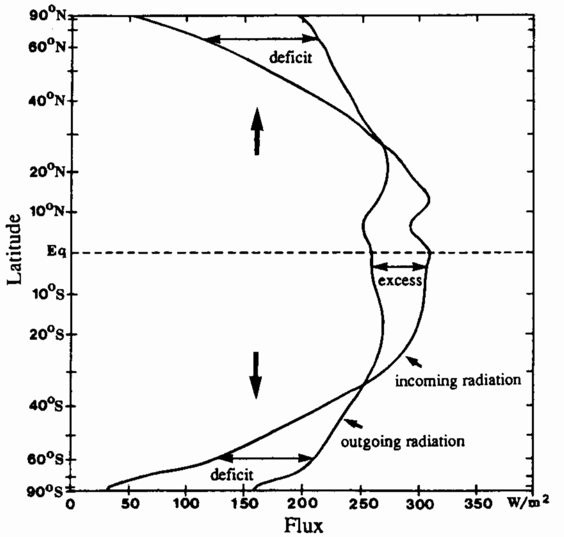


Figure 18-4 Averaged radiation flux by latitude, calculated from satellite data over the period 1974–1978. The latitude scale simulates the amount of surface area between latitude bands. Incoming radiation is the shortwave solar radiation absorbed by the earth and atmosphere. Outgoing radiation is the longwave radiation leaving the atmosphere. (From Winston et al., 1979.)

and partly incorrect, insofar as these meridional circulations extend only to 30° of latitude. North of 30°N and south of 30°S, opposite circulations are observed, up to 60°, beyond which circulations in the sense predicted by Hadley are again found. Because the convective circulations theorized by Hadley follow our intuition, they are generally called *direct cells*. Those direct cells bordering the equator are also called *Hadley cells*. In contrast, the reverse circulations found at midlatitudes bear the name of *indirect cells*. Our purpose here is to explain, in some qualitative manner, why such oppositely directed meridional circulations exist. The story is not simple, invoking the aggregate effect of the transient weather systems of the midlatitudes.

To begin, we note that, although a single direct convective cell could theoretically span an entire hemisphere, numerous studies have indicated that such would be unstable. The strong zonal flow in thermal-wind balance with the large meridional temperature gradient would be baroclinically unstable. In fact, the more moderate zonal winds accompanying the alternating circulation structure that exists on the earth are themselves unstable, as the vagaries of the midlatitude weather plainly show. According to our discussion of baroclinic instability (Section 16-3), such instabilities develop into coherent vortex systems that are capable of transferring heat meridionally. At midlatitudes, therefore, the transfer does not take place in a vertical loop, as in a Hadley cell, but via the horizontal circulation of each vortex (warm air moving poleward on one side and cold air flowing equatorward on the other). We will now show how the cumulative action of such weather systems at midlatitudes can perform the required poleward transfer of heat so effectively to reverse the meridional circulation in the vertical plane.

The analysis starts with a few modifications of the governing equations. First, the density departure from the reference ρ_0 is expressed in terms of a temperature anomaly T (measured from the temperature corresponding to the reference density): $\rho = -\rho_0 \alpha T$, where $\alpha = 1/T_0$ is the thermal-expansion coefficient. Then, viscosity and heat diffusivity are neglected, but a heat source or sink term is added in the temperature equation to represent the heat gain in the tropics and the heat loss at high latitudes. From (3-25) through (3-29), we have

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} - fv = -\frac{1}{\rho_0}\frac{\partial p}{\partial x}, \qquad (18\text{-}6a)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + fu = -\frac{1}{\rho_0}\frac{\partial p}{\partial y}, \qquad (18\text{-}6b)$$

$$\frac{\partial p}{\partial z} = \rho_0 \alpha g T, \qquad (18\text{-}6c)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0, \qquad (18\text{-}6d)$$

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z} = Q, \qquad (18\text{-}6e)$$

where Q is the aforementioned thermal forcing. Focusing exclusively on the Northern Hemisphere, we take Q positive at lower values of y (northward coordinate) and negative at higher values of y. Thus, the gradient $\partial Q/\partial y$ is negative. The choice of beta-plane equations based on a Cartesian coordinate system over more appropriate equations in spherical coordinates is justified in the spirit of a highly simplified analysis aimed at highlighting physical processes in a qualitative way.

We next define the zonal average as the mean over the allowed values of x at any given y and z levels and time t. The zonal averages of the linear equations (18-6c) and (18-6d) are immediate:

$$\frac{\partial \bar{p}}{\partial z} = \rho_0 \alpha g \bar{T}, \qquad (18\text{-}7)$$

$$\frac{\partial \bar{v}}{\partial y} + \frac{\partial \bar{w}}{\partial z} = 0, \qquad (18\text{-}8)$$

where the overbar denotes this zonal average. With a prime denoting the departure from the average (e.g., $u = \bar{u} + u'$) and with some use of (18-6d), the zonal average of (18-6b) can be expressed as

$$\frac{\partial \bar{v}}{\partial t} + \bar{v}\frac{\partial \bar{v}}{\partial y} + \bar{w}\frac{\partial \bar{v}}{\partial z} + f\bar{u} = -\frac{1}{\rho_0}\frac{\partial \bar{p}}{\partial y} - \frac{\partial}{\partial y}\overline{v'^2} - \frac{\partial}{\partial z}\overline{v'w'}.$$

The large meridional pressure gradient ($\partial \bar{p}/\partial y$) associated with the important northward decrease in temperature ($\partial \bar{T}/\partial y < 0$) is balanced by a significant zonal flow ($\bar{u}$). In contrast, the vertical circulation ($\bar{v}$, $\bar{w}$) is much weaker, as are the corresponding eddy fluxes ($\overline{v'^2}$, $\overline{v'w'}$). Thus, to a high degree of accuracy, the preceding may be reduced to

$$f\bar{u} = -\frac{1}{\rho_0}\frac{\partial \bar{p}}{\partial y}. \tag{18-9}$$

Together, the hydrostatic balance, (18-7), and the geostrophic relation, (18-9), provide the thermal-wind relation

$$f\frac{\partial \bar{u}}{\partial z} = -\alpha g\frac{\partial \bar{T}}{\partial y}, \tag{18-10}$$

which relates the vertical shear of the average zonal wind to the average meridional temperature gradient. With the temperature decreasing northward in the Northern Hemisphere ($\partial \bar{T}/\partial y < 0, f > 0$), the wind shear is positive ($\partial \bar{u}/\partial z > 0$), indicating that the winds must become more westerly (eastward) with altitude.

Finally, we apply the zonal average to the remaining two equations, (18-6a) and (18-6e), to obtain

$$\frac{\partial \bar{u}}{\partial t} + \bar{v}\frac{\partial \bar{u}}{\partial y} + \bar{w}\frac{\partial \bar{u}}{\partial z} - f\bar{v} = -\frac{\partial}{\partial y}\overline{u'v'} - \frac{\partial}{\partial z}\overline{u'w'},$$

$$\frac{\partial \bar{T}}{\partial t} + \bar{v}\frac{\partial \bar{T}}{\partial y} + \bar{w}\frac{\partial \bar{T}}{\partial z} = \bar{Q} - \frac{\partial}{\partial y}\overline{v'T'} - \frac{\partial}{\partial z}\overline{w'T'}.$$

According to our previous remarks, the eddy fluxes of momentum and heat associated with the horizontal circulations in the weather systems ($\overline{u'v'}$ and $\overline{v'T'}$) are anticipated to be important, and the corresponding terms are retained. On the other hand, the vertical eddy fluxes ($\overline{u'w'}$ and $\overline{w'T'}$) are neglected. Except for the mean vertical advection of temperature ($\bar{w}\partial \bar{T}/\partial z$) because there is a substantial vertical stratification, mean meridional and vertical advections are unimportant, compared to the meridional eddy transports. In the light of these considerations, the preceding two equations may be reduced to

$$\frac{\partial \bar{u}}{\partial t} - f\bar{v} = -\frac{\partial}{\partial y}\overline{u'v'}, \tag{18-11}$$

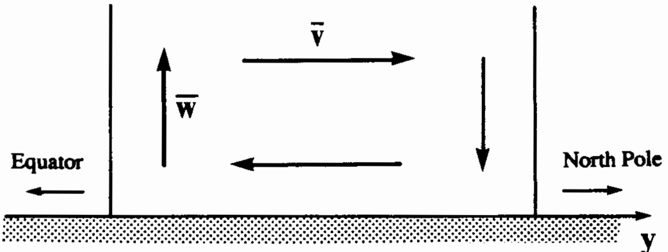
$$\frac{\partial \bar{T}}{\partial t} + \frac{N^2}{\alpha g}\bar{w} = \bar{Q} - \frac{\partial}{\partial y}\overline{v'T'}. \tag{18-12}$$

Here, we have introduced the stratification frequency N via $N^2 = \alpha g \partial \overline{T} / \partial z$.

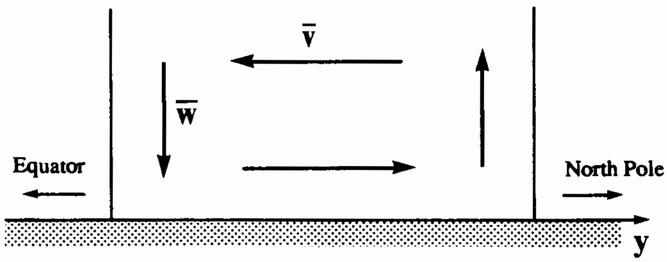
Forming f times the z-derivative of the first equation plus αg times the y-derivative of the second, to eliminate the time derivatives via (18-10), we obtain

$$\frac{\partial \overline{w}}{\partial y} - \frac{f^2}{N^2} \frac{\partial \overline{v}}{\partial z} = \frac{\alpha g}{N^2} \frac{\partial \overline{Q}}{\partial y} - \frac{\alpha g}{N^2} \frac{\partial^2}{\partial y^2} \overline{v'T'} - \frac{f}{N^2} \frac{\partial^2}{\partial y \partial z} \overline{u'v'}. \quad (18\text{-}13)$$

In this last equation, the sign of the left-hand side is directly related to the direction of the average circulation in the vertical plane. For simplicity, let us restrict our attention again to the Northern Hemisphere. In a direct cell (Figure 18-5a), $\overline{w}$ decreases northward and $\overline{v}$ increases upward, together yielding a negative left-hand side. On the other hand (Figure 18-5b), an indirect cell corresponds to a positive left-hand side.



(a)



(b)

Figure 18-5 Atmospheric circulation in the meridional-vertical plane: (a) direct cell (also called Hadley cell) with $\partial\overline{w}/\partial y < 0$ and $\partial\overline{v}/\partial z > 0$, and (b) indirect cell (also called Ferrel cell) with opposite circulation.

According to the right-hand side of (18-13), there are three competing mechanisms influencing the sense of the circulation. In the tropical regions, away from the eddy activity of the midlatitudes, the dominant factor is heating ($\overline{Q}$ term). Because the rate of heating decreases northward ($\partial \overline{Q} / \partial y < 0$), this term is negative, and the circulation in the vertical plane is in the direct sense. This occurs up to 30°N, and the circulation driven by thermal convection is the Hadley cell. The northerly (equatorward) winds along the surface ($\overline{v} < 0$) deflect to the right under the action of the Coriolis force, resulting in easterly (westward) zonal winds ($\overline{u} < 0$). These form the *trade winds*.

North of approximately 30°N, where the eddy activity is most intense, the corresponding terms ($\overline{v'T'}$ and $\overline{u'v'}$) dominate the right-hand side of (18-13). Both induce an indirect circulation. This is easy to see with the $\overline{v'T'}$ term and a little harder to see with the $\overline{u'v'}$ term. The average product $\overline{v'T'}$ is proportional to the meridional heat flux of the eddies. Since this net heat flux must be northward, warm anomalies ($T' > 0$) are, in general, moved northward ($v' > 0$); cold anomalies, on the other hand, are advected southward ($T' < 0$, $v' < 0$), yielding a net positive $\overline{v'T'}$ correlation. Because the eddy activity is most intense at midlatitudes, the term $\overline{v'T'}$ reaches a maximum there. Thus the second derivative $\partial^2\overline{v'T'}/\partial y^2$ must be negative. Preceded by a minus sign in (18-13), the corresponding term is positive.

The convergence of warm and cold air masses aloft creates a locally intensified gradient of temperature; in thermal-wind balance with this gradient is the polar-front jet stream (Figure 17-1) that flows eastward. The maintenance of this jet in spite of the eddy activity requires a continuous influx of eastward momentum (i.e., positive u' anomalies must be transported to that latitude). This is effected by the eddies, which import positive momentum anomalies from the south ($u' > 0$, $v' > 0$) and from the north ($u' > 0$, $v' < 0$). Thus, the average $\overline{u'v'}$ is positive south of the jet and negative north of it, and the derivative $\partial\overline{u'v'}/\partial y$ must be negative. At the surface, where the jet stream is not found, the correlation $\overline{u'v'}$ is much less important, and we conclude that $\partial\overline{u'v'}\,\partial y$ is increasingly negative with altitude, namely, $\partial^2\overline{u'v'}/\partial y\partial z$ is negative. Preceded by a minus sign in (18-13), this term adds to the positive contribution of the

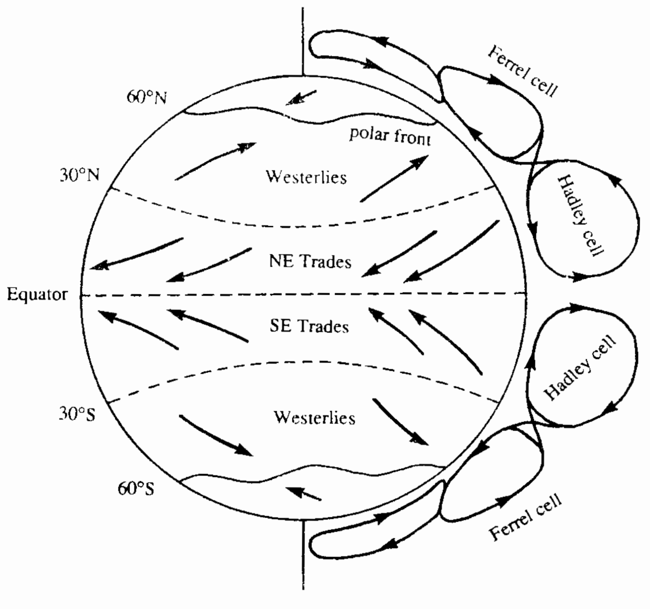


Figure 18-6 Sketch of the general atmospheric circulation, composed of direct (Hadley) and indirect (Ferrel) cells in the meridional direction and of alternating winds in the zonal direction.

other eddy-flux term, and together they overcome the $\overline{Q}$ term. The result is an indirect cell, called the *Ferrel cell*. A corresponding indirect cell is found in the Southern Hemisphere. These Ferrel cells extend to approximately 60°; beyond that, the eddy activity yields to a thermal circulation in the vertical and direct cells exist (Figure 18-6).

The alternation of direct and indirect cells in the meridional direction leads to a similar alternation in surface zonal winds: from the easterly trades to the prevailing westerlies, to the polar easterlies (Figure 18-6).

18-4 THE OCEAN AS A REGULATOR

We saw in Chapter 8 how the wind reversal from trades to easterlies around 30°N drives the subtropical ocean circulation, including western boundary currents such as the Gulf Stream and Kuroshio. These oceanic gyres and similar but weaker counterparts in the Southern Hemisphere carry warm waters poleward and return colder waters equatorward, therefore sharing with the atmosphere the task of transporting heat poleward. The ocean also transports heat poleward by a vertical circulation that is, in essence, a subsurface Hadley cell. Cold waters are formed by cooling at high latitudes and sink; these deep water masses spread throughout the ocean basins and slowly upwell, passing into the surface circulation that will eventually return them to high latitudes. Because of the role played by salinity in controlling the rate and depth of sinking, this large-scale circulation in the abyssal ocean is called the *thermohaline circulation*. Together, the subtropical gyres, the thermohaline circulation, and the equatorial upwelling contribute to a sizable heat transport toward the poles.

Estimates derived from numerical simulations (Manabe, 1969) and from accumulated observations (Vonder Haar and Oort, 1973; see Figure 18-7) all suggest that at midlatitudes, the ocean may transport as much as half of the required heat flux. One reason for this behavior is the high specific heat of water (four times greater than that of air, per kilogram, or more than 3000 times that of air per volume!), which implies that moderate temperature anomalies in the ocean can transport large quantities of heat. It follows that our planet would be very different without its oceans. First, because the atmosphere is less efficient at transporting heat, the tropical regions would be much hotter and the polar regions, much colder. Second, the transient eddies at midlatitudes would be much more active, causing weather to be much more variable with more severe storms. Third, because the oceans act as a buffer by storing heat during the summer and releasing it slowly during the winter, our planet without its oceans would experience much larger seasonal variations. In other words, the oceans serve as a vital regulator of climate.

The present regulating role of the oceans, as we have just described (tempering atmospheric variations over the latitudes and the seasons), does not necessarily imply, however, that no matter what happens to the atmosphere, the oceans will act as a buffer and moderate the impact of the change. We must recognize that our climate is in a delicate balance. The present situation, in which noticeable changes to the atmospheric chemistry attributed to human activities have been recorded, may lead to atmospheric

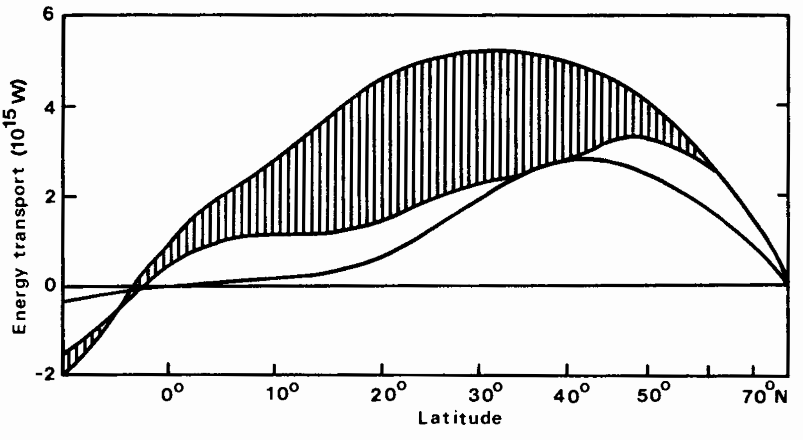


Figure 18-7 The northward transport of energy (in units of petawatt = 10^{15} W) as a function of latitude. As in Figure 18-4, the latitude scale simulates the amount of area between latitude bands. The outer curve is the net transport deduced from radiation measurements. The middle curve is the atmospheric contribution, leaving by subtraction the shaded area to correspond to the part transported by the ocean. The lowest curve is the fraction of the atmospheric transport attributable to transient eddies (weather patterns). Although these curves are based on the best estimates available, the probable errors may be quite large. (From Vonder Haar and Oort, 1973, as adapted by Gill, 1982.)

modifications that—if they occur—will affect the oceans. In turn, the oceanic changes may provide a restoring tendency (buffer) or may aggravate the situation (positive feedback). The matter is serious, for oceanic temperature changes as small as a few degrees would translate into very important (and thus potentially disastrous) atmospheric modifications. The following section discusses a few specific issues.

18-5 GREENHOUSE EFFECT

A serious concern nowadays is the effect of increased atmospheric CO_2 concentrations on the earth's heat budget. In particular, some fear that we are on the verge of a global warming with catastrophic consequences for humanity.

The argument goes as follows. Carbon dioxide (CO_2) absorbs longwave radiation around 13 μm and thus intercepts the earth's outgoing radiation, contributing to the greenhouse effect. (Carbon dioxide is called a *greenhouse gas*.) The burning of fossil fuels, specifically, and industrial activities, generally, have increased the amount of CO_2 in the atmosphere. Observations taken on a Hawaiian island since 1958 (Figure 18-8), considered to be representative of a large area of the Northern Hemisphere, show an evident increase from about 315 ppm (parts per million) in 1958 to 350 ppm in 1988. Preindustrial concentrations are estimated at 270 to 280 ppm, and there is little doubt that atmospheric concentrations of carbon dioxide will continue to rise in the forseeable future. With more CO_2, the atmosphere is more opaque to outgoing longwave radiation,

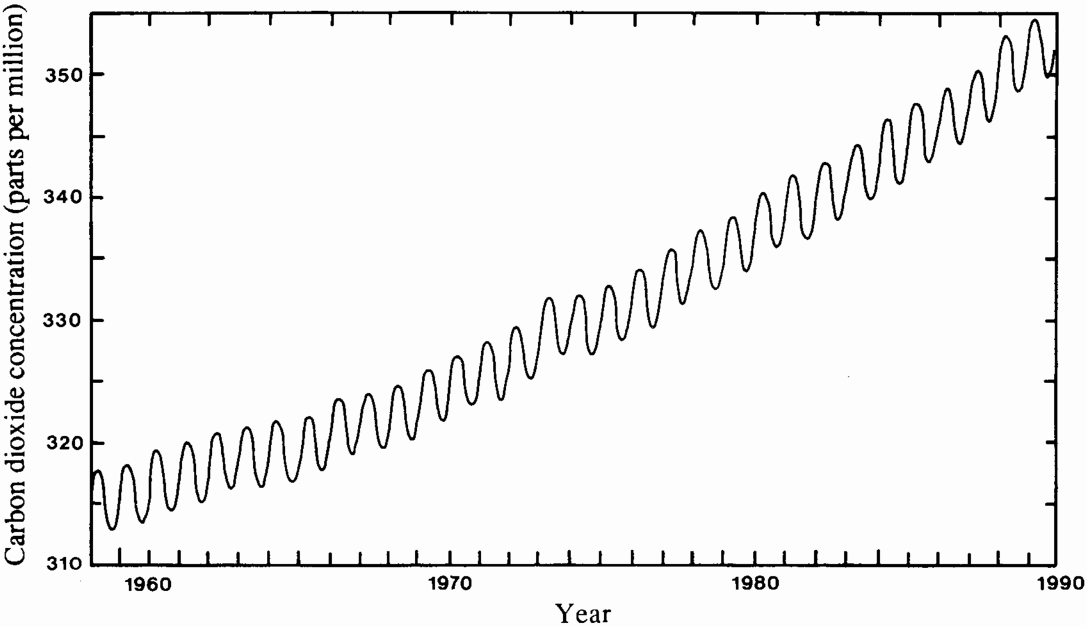


Figure 18-8 Mean monthly concentration of atmospheric carbon dioxide (CO_2) at Mauna Loa, Hawaii. Note the gradual rise of concentration, in addition to the seasonal oscillation. (From Geophysical Monitoring for Climate Change, NOAA, Washington, D.C.)

and the greenhouse radiation loop is intensified. An immediate conclusion, or so it seems, is that the temperature on the surface of the earth will rise. The consequence would be a global warming, and this explains why the expressions *greenhouse effect* and *global warming* are frequently used at the same time. (Note that global warming is not synonymous with greenhouse effect, the former being an eventual and undesirable consequence of an increased intensity of the latter, which normally is beneficial to life.) Our purpose here is to discuss briefly the validity of the preceding argument and to quantify the eventual temperature increase.

First and foremost, it is important to recognize that water (as droplets in clouds and water vapor) is by far a more effective greenhouse agent than carbon dioxide. Specifically, it accounts for the low transmission coefficient β_2 (= 5%) of the atmosphere in the infrared range (Section 18-12). The infrared radiation from the earth's surface spans a range of wavelengths (5 to 50 μm), some intervals of which are completely blocked by water absorption; in the remaining wavelength bands (called *windows*), water appears as transparent. Because its chemistry is different, CO_2 causes partial absorption at 13 μm, in one of the windows. Raising the amount of water in the atmosphere should not cause an increase in greenhouse effect, because sufficient water levels already exist to block totally the radiation in the bands obstructed by water. On the other hand, increasing carbon-dioxide levels will block, to a greater extent, some of the radiation not absorbed by water. Let us keep in mind, however, that there will always remain wavelength bands that are affected by neither water nor carbon dioxide.

An effect of increased atmospheric CO_2 is thus to reduce the amount of earth's surface radiation transmitted by the atmosphere—that is, to lower the coefficient β_2 further. Although this transmission coefficient will not vanish under the action of increased CO_2 alone, as argued in the previous paragraph, it is worth considering a worst-case scenario in which it is put to zero. With $\beta_2 = 0$ and thus $T_3 = 0$, the amount of radiation emitted by the earth's surface becomes, from (18-4) and (18-5),

$$E_2 = \frac{0.64\ A_1 + A_2}{0.36} - Q = 451.9\ \text{W/m}^2,$$

to which the corresponding temperature is (from $\sigma T^4 = E_2$):

$$T = 299\ \text{K} = 26°\text{C}.$$

Thus, a worst-case scenario is a 7°C rise in globally averaged temperature. This ought to be an overestimate, because (1) carbon dioxide, regardless of its concentration, still leaves open some radiation windows, and (2) it is not certain that enough fossil-fuel reserves exist to provide, once all are burned, enough CO_2 to block all radiation in the CO_2-absorbing band.

However (such *howevers* are frequent in discussions of a possible global warming!), if the temperature increases, other elements of the heat budget will be affected, and it is not at all clear (from simple arguments) whether the tendency is toward greater or lesser warming. One component of the heat budget that is most likely to be modified is the hydrological cycle. On a warmer earth, there would be more evaporation and, for the balance, more precipitation. Therefore, the amount of latent heat transferred from the earth's surface to atmosphere would increase, short-circuiting the greenhouse effect to a large degree. Supposing that it increases by 10%—that is, from $Q = 113.6$ to 125.0 W/m^2—we calculate (still with $\beta_2 = 0$) an earth-surface flux $E_2 = 440.5$ W/m^2, corresponding to $T = 297$ K = 24°C, or a smaller 5°C increase. Similarly, a 20% increase in the intensity of the hydrological cycle would yield $T = 22$°C, or a 3°C rise. The conclusion from this line of thought is that the hydrological cycle acts as a strongly restoring mechanism.

But speculations, however reasonable, must be put to the test. In view of the obvious impossibility to stage real climate-change experiments, scientists resort to computer simulations with numerical models. Starting in the 1960s, Syukuro Manabe (see the biography at the end of this chapter) and several others developed such numerical models, of various degrees of complexity, to quantify the climate response to increasing levels of atmospheric carbon dioxide (among other models: Manabe et al., 1965; Hansen et al., 1988; Manabe et al., 1991). For objective model-to-model comparisons and for the sake of obtaining specific numbers, the problem is typically framed as the following question: What effects would a doubling of present CO_2 concentrations have on our climate? Answers agree that the globally averaged temperature on the earth the surface would increase but disagree on the size of this increase, with values ranging between 1.5°C and 5°C (National Research Council, 1983; Lindzen, 1990). Differences between model results are attributed to our yet imprecise knowledge of which physical processes among the many possible candidates must be included in the calculations, as well as to our present inability, because of computer limitations, to simulate with the necessary accuracy short-term processes (e.g., cloud formations and oceanic eddies). Also, as Manabe et al. (1991) argue, climatic inertia due primarily to a delayed oceanic response requires nonequilibrium studies, and consequently the rate at which carbon-dioxide concentrations increase matters.

Although the various models agree on a global temperature increase, they are in sharp disagreement over regional variations, except in polar regions where they systematically project temperature increases greater than the global average, especially in wintertime (Lindzen, 1990). Ironically, actual records of temperature over the Atlantic Arctic since 1900 do not support this conclusion (Rogers, 1989, quoted in Lindzen, 1990). In summary, much work remains before numerical models provide consistent and reliable answers to the question of a possible global warming, but in the meantime, their results should serve as warnings for what could happen. A good and succinct overview of the debate over global warming can be found in Lindzen (1990).

PROBLEMS

18-1. Consider the regular gardening greenhouse and idealize the system as follows: The ground and glass act as blackbodies, the air plays no role, the ground absorbs all radiation, and the glass is perfectly transparent to shortwave (visible) radiation and totally opaque to longwave (heat) radiation. Further, the glass emits its radiation upward and downward in equal parts. Compare the ground temperature inside the greenhouse with that outside. Then, redo the exercise for a greenhouse with two layers of glass separated by a layer of air.

18-2. Consider the crudest heat budget for the earth (without atmosphere and hydrological cycle) and assume the following dependency of the albedo on temperature: At low temperatures, much ice and clouds cover the earth, yielding a high albedo, whereas at high temperatures, the absence of ice and clouds reduce the albedo to zero. Taking the functional dependence as

$$\alpha = 0.5 \quad \text{for } T \leq 250 \text{ K},$$

$$\alpha = \frac{270 - T}{40} \quad \text{for } 250 \text{ K} \leq T \leq 270 \text{ K},$$

$$\alpha = 0 \quad \text{for } 270 \text{ K} \leq T,$$

solve for the earth's average temperature T. Discuss the several solutions.

18-3. Using the global heat budget of the earth model, complete with an atmospheric layer and a hydrological cycle, explore a worst-case scenario whereby elevated concentrations of greenhouse gases completely block the transmission of longwave radiation from the earth's surface, the intensity of the hydrological cycle is unchanged, and the anticipated global warming has caused the complete melting of all ice sheets, effectively eliminating all reflection by the earth's surface of shortwave solar radiation. What would then be the globally averaged temperature of the earth's surface? (Except for those transmission and reflection coefficients that need to be revised, use the parameter values quoted in the text.)

SUGGESTED LABORATORY DEMONSTRATION

Equipment

Three identical thermometers (small size), two glass jars with lids (able to contain one thermometer), white and black paper (cut to diameter and height of jar).

Experiment

Place one thermometer in each jar and, behind the thermometer, the white or black paper. Then, expose the two jars and the third thermometer alone to sunlight (for example on the still of an open window in the classroom). After some time, compare the thermometer readings. Explain the differences.

Syukuro Manabe

1931 –

Syukuro Manabe has pioneered computer simulations of the earth's climate and hydrologic cycle. Relying upon the assumption of radiative, convective equilibrium, he was the first to demonstrate how various greenhouse gases, such as water vapor, carbon dioxide and ozone help maintain the thermal structure of the atmosphere. This study was a major stepping stone towards the successful simulation of the global climate by a general circulation model of the atmosphere. With Kirk Bryan and collaborators in the late 1960s, he also developed the first computer model coupling oceans and atmosphere and advocated the use of such models for the study of climate dynamics. His original modeling studies on the greenhouse effect and the link between increasing levels of atmospheric carbon dioxide and global warming have brought him well-deserved international recognition. (*Photo credit: S. Manabe.*)