The Energy Cycle of the Earth

The solar energy absorbed by the earth is eventually reradiated into space as heat. Meanwhile it is distributed over the surface of the earth by the circulation of the atmosphere and the oceans

by Abraham H. Oort

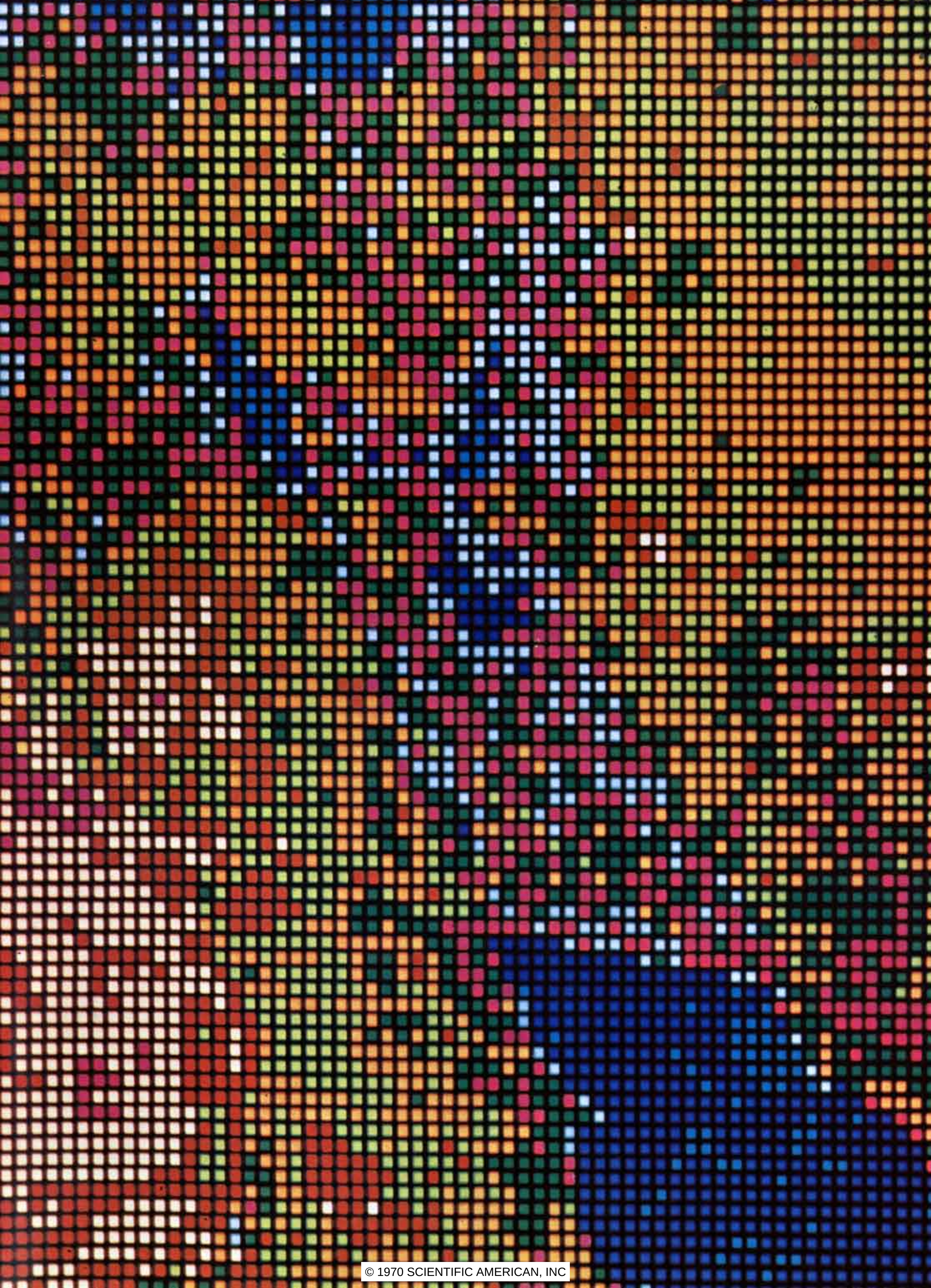
All life on the earth is of course ultimately powered by the sun, and accordingly it is strongly affected by variations of the incoming solar radiation over the globe. The distribution of sunlight with latitude determines to a great extent the location of the major climatic zones—tropical, temperate and polar—and these zones in turn set broad geographic limits to the different forms of terrestrial life.

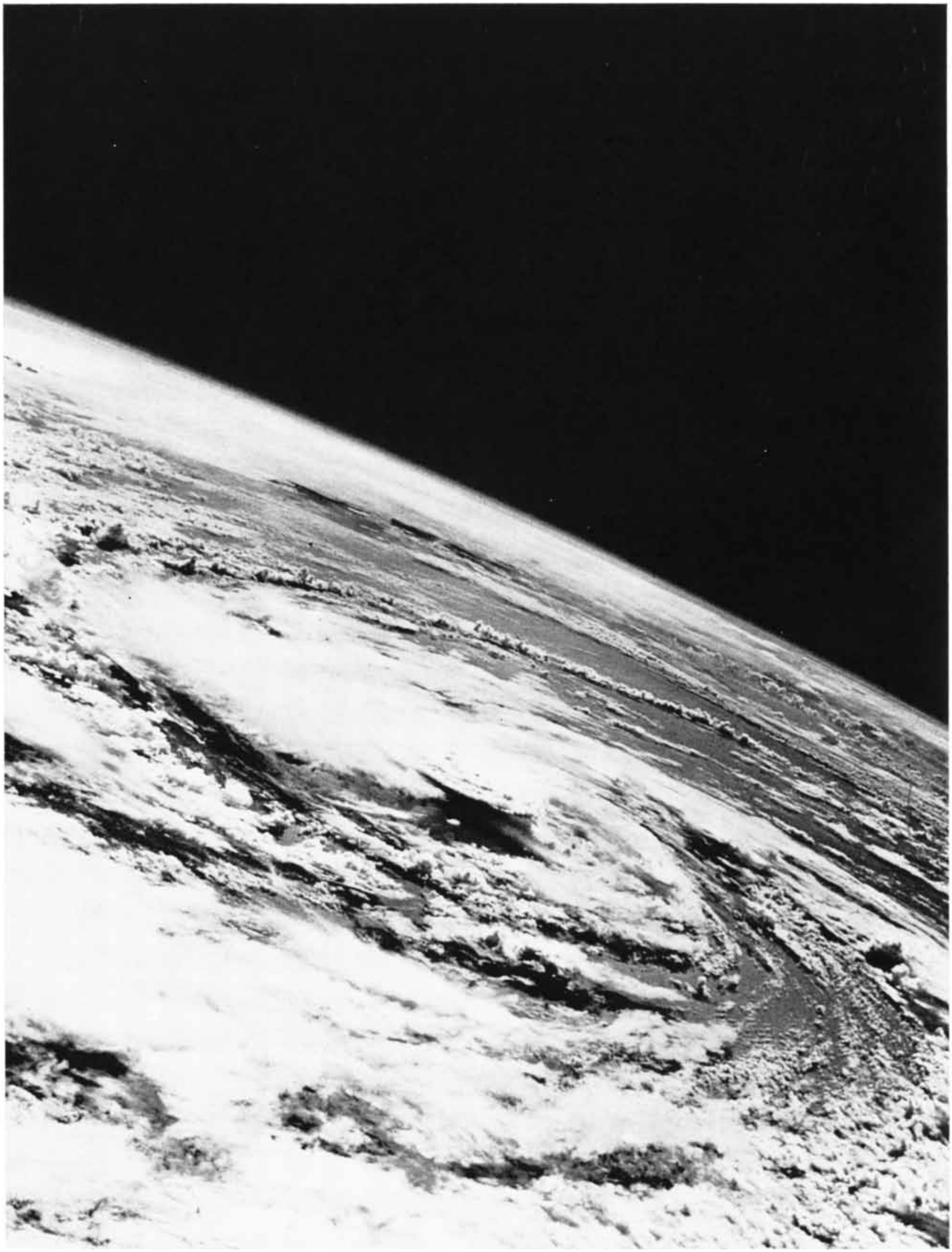
What is less familiar is the central function of the atmosphere and the oceans in redistributing the incoming solar energy and hence in determining the "macroclimate" of the earth. The importance of the circulation of the atmosphere and the oceans to the operation of the biosphere becomes apparent when one considers that present forms of life could not endure the harsh climate that would exist if conditions of radiative equilibrium were to prevail at all latitudes (that is, if the incoming solar radiation to a zone were exactly balanced by the outgoing terrestrial radiation from that zone). This article is devoted not only to an examination of the character of the incoming short-wave radiation and the outgoing long-wave radiation but also to an attempt to trace the cycle of the solar energy from the time it enters the atmosphere as sunlight until it finally finds its way back into space as heat. At the end of the article I shall take up the question of the possible effects of man's intervention in these vast energy processes.

When the sun is over the Equator on March 21 and September 23 (the equinoxes), a maximum amount of solar radiation is received at the Equator [*see illustration on page 58*]. On the same dates the radiation received at the north and south poles is practically zero. This symmetrical decrease of radiation with latitude toward both poles only occurs, however, during the transition seasons, spring and fall. In the summer hemisphere, for example, there is almost no meridional (north-south) heating gradient. Even more surprising is the fact that the 24-hour average sunshine has a maximum value at the summer pole, not at the subsolar point in the Tropics! This of course is owing to the permanent daylight at the summer pole. From a consideration of these factors alone one would expect significant differences in the large-scale circulation between the summer and the winter hemispheres. In addition one would expect climatic effects related to the variation of incoming radiation with local time in each hemisphere [*see illustration on page 59*]. Diurnal changes (that is, changes with a period of 24 hours) in the wind, temperature and humidity are only important, however, close to the ground and at high levels in the atmosphere. Locally the interaction of land and sea breeze effects may also play a role, but the overall atmospheric circulation cannot respond well to such short-period phenomena. This is even truer of the oceanic circulation. In addition to the imposed diurnal and annual periodicities in the incoming solar radiation, one finds a slight semiannual variation of insolation in the Tropics, where the sun passes overhead twice during the year.

How is the solar energy transmitted and transformed once it enters the top of the atmosphere? Averaged over the globe about 30 percent of the radiation is either scattered back by the constituents of the atmosphere or directly reflected by clouds or the earth's surface. This portion of the solar energy is lost into space and cannot be used to generate atmospheric motions. About 50 percent of the incoming radiation finally reaches the ground or ocean, where it is absorbed as heat. The properties of the surface determine the thickness of the layer over which the available heat is distributed. In the case of an ocean surface wave motions are quite effective in distributing the heat through a thick layer, sometimes extending down to a depth of 100 meters. The diurnal variation in temperature of the ocean surface itself

MOSAIC OF COLORED SQUARES on the opposite page is actually a "map" showing the relative infrared reflectance of various land and water surfaces in a region of the Middle East. The data used to construct the map were obtained at noon on May 4, 1969, by means of a high-resolution scanning infrared radiometer on board the unmanned artificial earth satellite *Nimbus 3.* The data were digitized, adjusted for differences in sun angle and displayed in a format in which the color of each square represents a range of relative reflectance. In assigning different colors to each range an attempt was made to render the scene in "natural" colors. Thus the lowest ranges of relative reflectance, which correspond generally to water surfaces, are represented by different shades of blue. Areas of intermediate reflectance, corresponding roughly to vegetated regions, are green. Highly reflective desert areas are beige. The large body of water at lower right is the Red Sea. At its northern end the reflectance is modified by haze, obscuring much of the gulfs of Suez and Aqaba, which flank the Sinai Peninsula. The blue area at top left is the Mediterranean Sea. The triangular green area adjacent to it is the Nile delta. The string of green squares at bottom left represents the lake forming in the Nile River valley as a result of the construction of the Aswan Dam. The map was produced as part of a study conducted by Norman H. MacLeod of the National Aeronautics and Space Administration in an effort to develop a quantitative technique for observing the earth in terms of the relative reflectance of its parts.





HURRICANE GLADYS was photographed by the *Apollo 7* astronauts as it approached the west coast of Florida on the morning of October 17, 1968. The view is toward the southeast with Cuba in the distant background. The lack of the usual high cloud cover made it possible to view the spiral lower cloud structure of this cyclonic storm in considerable detail. Traveling cyclones (of which hurricanes are a particularly violent form) contribute to the net poleward transport of heat in the middle latitudes and thus help to moderate the harsh climate that would exist on the earth if conditions of radiative equilibrium were to prevail at all latitudes.

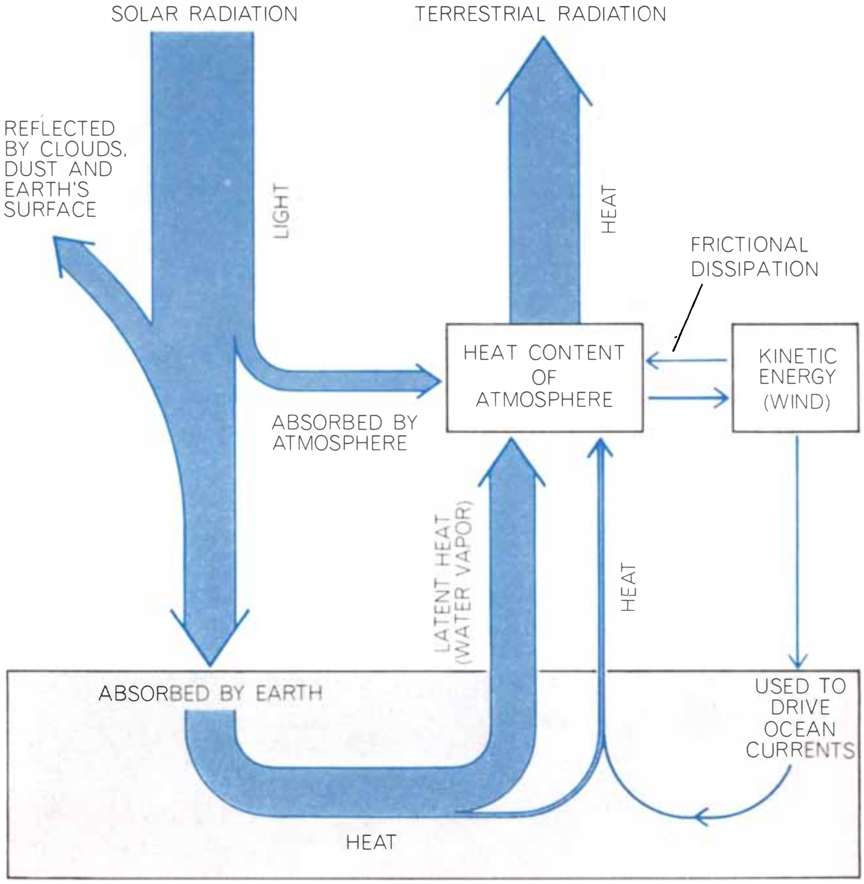
is thus generally less than 1 degree Celsius. The situation on land depends not only on the diurnal amplitude of the incoming radiation but also on the properties of the soil (for example its wetness) and the presence or absence of vegetation. The energy transfer down into the ground occurs through the slow process of molecular heat conduction. Over bare ground the diurnal temperature range at the surface can amount to several tens of degrees Celsius, but the temperature change is hardly noticeable below a depth of half a meter.

What happens to the remaining 20 percent of the incoming solar radiation that is apparently absorbed on its path through the atmosphere? Here it is necessary to consider the spectrum of the incoming and outgoing radiation [*see top illustration on page 60*]. The emission spectrum of the sun roughly resembles that of a "black body" radiating at a temperature of 6,000 degrees Kelvin. (A black body is defined as one that absorbs all the radiation falling on it.) In the visible portion of the spectrum (wavelengths between .4 and .7 micron), where the maximum influx of solar energy takes place, the radiation can penetrate almost without loss down to the earth's surface except where clouds are present. High in the atmosphere ordinary oxygen (O_2) and ozone (O_3) molecules absorb an estimated 1 to 3 percent of the incoming radiation. This absorption occurs in the ultraviolet portion of the spectrum and effectively limits the penetrating radiation to wavelengths longer than .3 micron. Although this effect is relatively small, it is important because it is the main source of energy for the circulation above 30 kilometers [see "The Circulation of the Upper Atmosphere," by Reginald E. Newell; SCIENTIFIC AMERICAN, March, 1964]. Moreover, the absorption at these levels shields the biosphere from the damaging effects of ultraviolet radiation. At wavelengths longer than one micron most of the atmospheric absorption is due to water vapor, dust and water droplets in clouds. This process operates in the lower troposphere and involves most of the remaining 20 percent of the total incoming radiation.

In spite of certain long-term climatic changes climatological records do not show an appreciable net heating or cooling of the earth and its atmosphere. Therefore the earth must emit an amount of radiation equal to the radiation absorbed. A characteristic shift to longer wavelengths does take place, however, since the earth radiates at an effective black-body temperature of about 255 degrees K., a very low value compared with the sun's black-body temperature of 6,000 degrees. The earth's emission occurs throughout a broad range of wavelengths with a flat maximum at about 12 microns. In this range of the spectrum the atmosphere is not transparent. Water vapor, ozone and carbon dioxide absorb significant amounts of long-wave radiation.

If one now calculates the vertical transfer of solar and terrestrial radiation using the observed temperature and humidity structure, one finds that the atmosphere is not in local radiative equilibrium. The net effect due to solar and terrestrial radiation alone would be an intense heating of the earth's surface and a cooling of the atmosphere at the rate of up to two degrees C. per day, depending on the height. In reality the air is prevented from cooling by the vertical transfer of heat directly from the earth's surface and by the release of heat through the condensation of water vapor. It is at this point that the dynamics of the atmosphere begin to play an important role.

The transport of energy upward into the atmosphere forms the major energy supply for the atmospheric heat engine. A large portion of this energy, however, is "latent" (that is, in the form of water vapor), and it is used to raise the atmospheric temperature only when condensation takes place. Close to the surface the energy transport occurs through evaporation of water, through heat conduction and through the transfer of long-wave radiation. At a certain height above the surface turbulent eddies mix the water vapor and heat further upward. The scale of the effective eddies increases with distance from the surface, finally growing to convective clouds of the cumulus type in the free atmosphere. This upward transfer of energy from the surface compensates for the radiative cooling of the atmosphere. A schematic diagram of the average energy cycle in the atmosphere reveals the important



ATMOSPHERIC HEAT ENGINE is averaged over the entire atmosphere in this diagram. The thickness of the arrows indicates approximately the strength of the various energy flows and conversion rates. As the diagram shows, the earth's surface acts as an indirect source of energy for the circulation in the atmosphere. Estimates of the efficiency of the atmospheric heat engine differ widely, depending on the energy inputs and outputs used to define efficiency. By one definition (the amount of energy used to generate ocean currents divided by the incoming solar energy) the efficiency of the system is less than 1 percent.

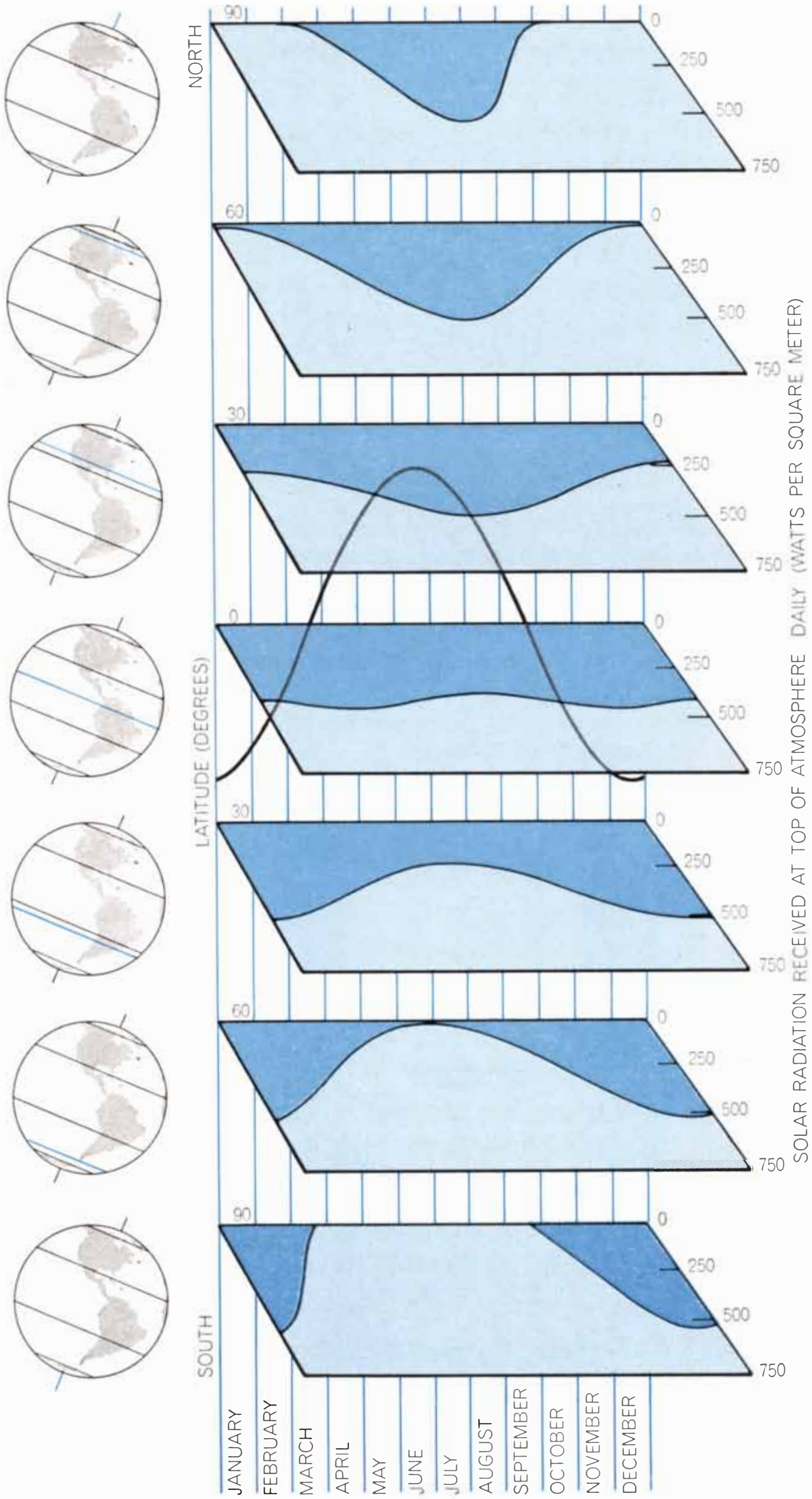
role of the earth's surface as the source of latent heat and sensible heat [*see illustration on preceding page*].

There is a significant difference in the character of the heating for the ocean and for the atmosphere. In the ocean the heating is applied at the top, which leads to stable conditions, whereas in the atmosphere the heating is applied at the bottom, giving rise to vigorous convection. The ocean currents, which are driven mainly by the winds, redistribute the absorbed solar heat horizontally and thereby influence in turn the pattern of the heat supply to the atmosphere that finally closes the cycle. The oceans and the atmosphere are strongly coupled systems and cannot very well be treated separately. The final circulation pattern is determined by the interaction of the two systems, each system influencing the other in a complicated cycle of events.

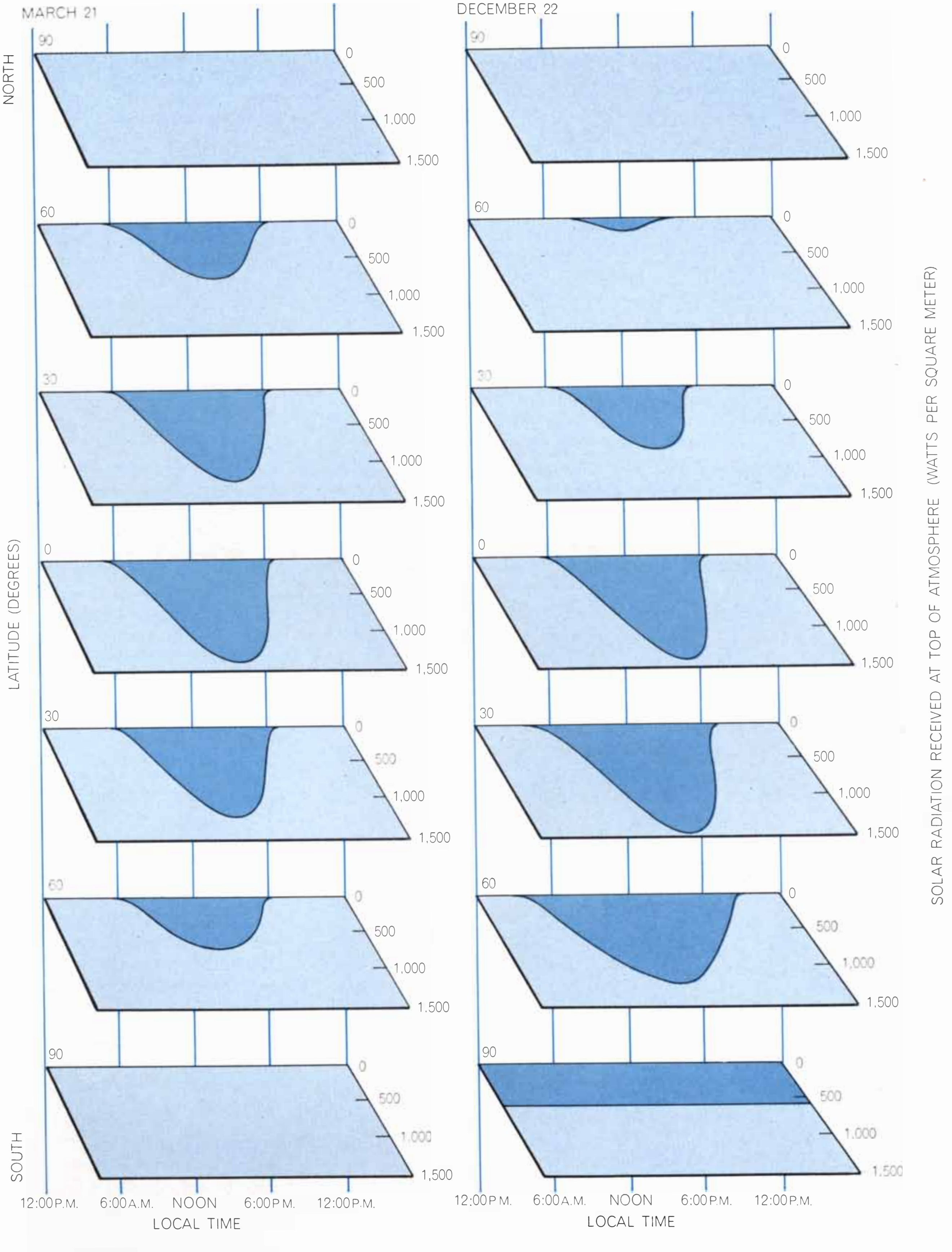
The effects of radiation and convection alone tend to maintain the proper energy balance for the earth as a whole, but the atmospheric and oceanic circulation must be considered if one wishes to explain the observed north-south temperature distribution [*see bottom illustration on page 60*]. The fact that the incoming solar radiation drops off more rapidly toward the winter pole than the outgoing terrestrial radiation does means that there is an excess in radiational heating in the summer hemisphere and a deficit near the winter pole. The storage of heat in the ocean during summer and the release of a large portion of this heat during winter has a moderating effect on the climate. Without an efficient north-south transfer of heat, however, the earth would still become very hot in the summer hemisphere and extremely cold at high latitudes in the winter hemisphere. The heating gradient constitutes the major driving force for the large-scale atmospheric currents and ultimately also for the oceanic currents. Judging from the existing temperature gradient, these circulations must be quite effective agents for transporting energy toward the winter pole.

What type of atmospheric and oceanic circulation patterns would develop as a consequence of such an imposed heating gradient? Let us limit the discussion for the time being to the winter situation. It is in this season that the north-south gradient in the solar heating is strongest and that the differences between the radiative equilibrium temperature and the observed temperature are at a maximum. What simple mechanism would suffice to transport heat poleward?

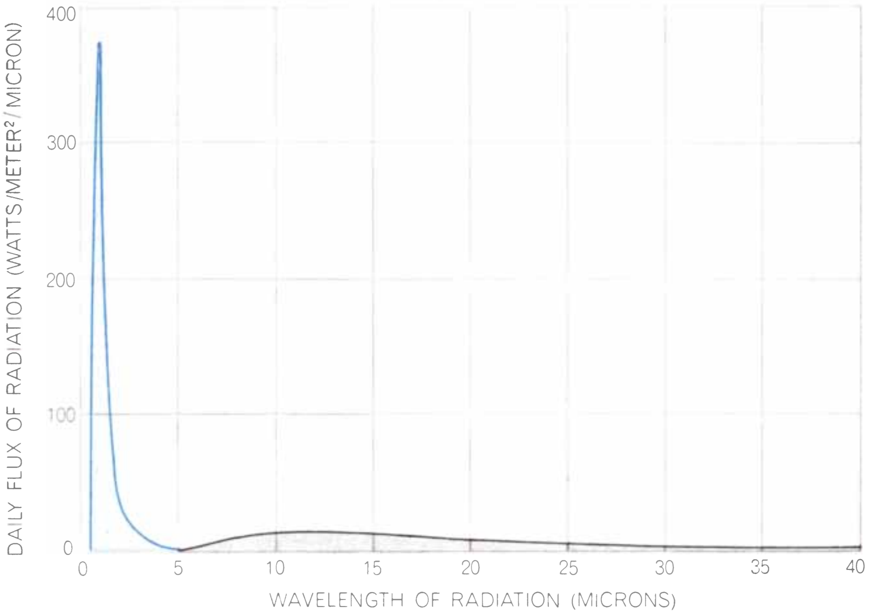
Let us first consider a model atmo-



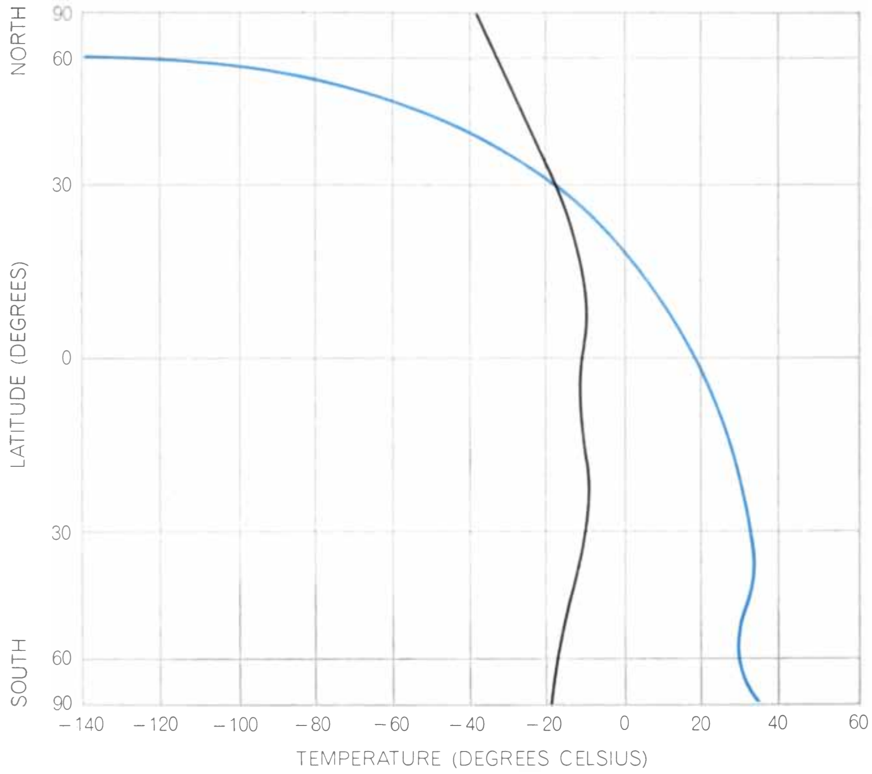
INCOMING SOLAR RADIATION (*dark color*) is shown in this three-dimensional chart at seven different latitudes as a function of month of the year. A large difference in the meridional (north-south) heating gradient exists between the winter and the summer hemispheres. In winter the gradient is very large, whereas in summer it practically disappears. The annual cycle in declination of the sun between 23 degrees north latitude (the Tropic of Cancer) and 23 degrees south latitude (the Tropic of Capricorn) is indicated by the solid black curve in the latitude plane (*background*). The radiation is averaged over all hours of the day. Data are from the Smithsonian Meteorological Tables, compiled by Robert J. List.



DIURNAL INSOLATION as a function of latitude varies widely according to the date. At the time of the equinoxes (around March 21 and September 23) the poleward decrease in the amount of incoming solar radiation with latitude is symmetrical with respect to the Equator and practically no radiation is received at either the North Pole or the South Pole (*chart at left*). At the solstices (around June 21 and December 22) the latitudinal differences in diurnal insolation between the two hemispheres are extreme (*chart at right*); the summer pole (*bottom*) receives sunlight 24 hours a day, whereas the winter pole (*top*) receives no sunlight at all.



APPROXIMATE EMISSION SPECTRA of the sun (*colored curve*) and the earth (*black curve*) are represented in this graph under the assumption that they radiate as "black bodies" with temperatures of 6,000 degrees and 250 degrees Kelvin respectively. The solar curve is corrected for the distance between the sun and the earth, for the fact that only one side of the earth is illuminated by the sun at any instant and finally for the mean albedo (reflectance) of 30 percent for the earth. The areas under the two curves are equal; in other words, the earth emits as much radiation as it absorbs. The important change in the character of this radiation from the short-wave to the long-wave part of the spectrum is evident.



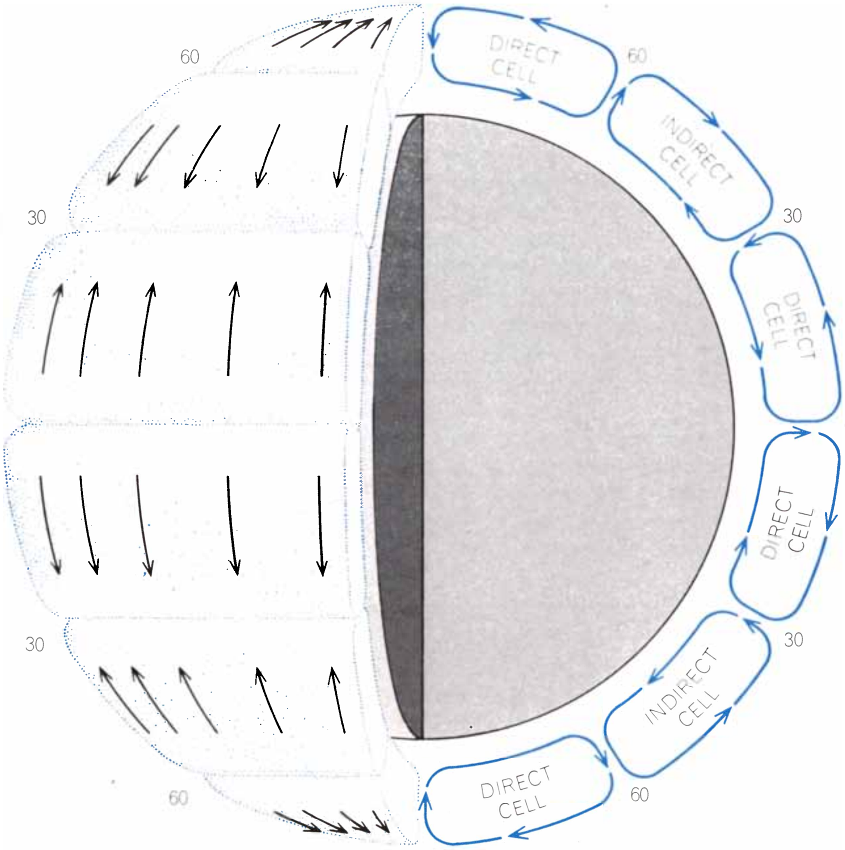
IMPORTANCE OF ATMOSPHERIC DYNAMICS in moderating the earth's climate is demonstrated by this graph, which compares the calculated radiative-equilibrium temperature for a "black" earth (*colored curve*) with the observed vertical mean temperature (*black curve*) as a function of latitude during January. At this time no sunshine reaches the earth north of the Arctic Circle; neglecting any lag effects due to the storage of heat, the radiative-equilibrium temperature in the polar cap would go down to absolute zero (–273.2 degrees Celsius), while the summer hemisphere would tend to become extremely hot.

sphere that has a uniform temperature and rotates at the same rate as the earth. If one starts to heat the air at low levels on the summer side of the Equator, the local temperature will rise and the air column will expand mainly in the vertical direction. This process will create at the upper levels a relatively high-pressure belt located over the "thermal" Equator. Next the north-south pressure gradient will force the equatorial air at all longitudes to move toward the low-pressure zone, mainly into the winter hemisphere, where initially vertical contraction occurred as a result of radiational cooling. The air will then slowly start to sink over a wide region in the winter hemisphere and will return to the Equator at low levels. The cycle will be closed finally through a rise of the air after it has arrived in the vicinity of the thermal Equator.

A simple cellular circulation of this kind, called a mean meridional circulation, would be completely symmetrical with respect to the earth's axis of rotation. The existence of one such cell in each hemisphere with rising warm air near the Equator and sinking cold air near the poles was originally postulated by the English meteorologist George Hadley in 1735. Such a cell is called a direct cell since it releases potential energy and converts it into kinetic energy. Later investigators, notably the 19th-century American meteorologist William Ferrel, showed that one actually needs three cells in each hemisphere to explain the important climatological features at the earth's surface [*see illustration on opposite page*]. This picture has been confirmed by many observational and theoretical studies and seems to represent rather well the annual mean conditions in the atmosphere. Recent and more detailed observations, however, have shown that only during the transition months in fall and spring is such an idealized circulation symmetrical with respect to the Equator realized. The asymmetry in heating during most of the year appears to favor the development of only one strong cell in the Tropics: the one in the winter hemisphere. This cell circulates on the average about 2×10^8 metric tons of air per second. At the same time the "summer" Hadley cell has shrunk to an insignificant size [*see illustration on pages 62 and 63*].

Let us consider in somewhat greater detail what energy transformations take place in the tropical Hadley cell. In its lower branch subtropical air flows close to the earth's surface toward the summer hemisphere with an average velocity of one or two meters per second. During the long journey equatorward heat and moisture are absorbed from the warm underlying ocean. This is the region of the trade winds. Near the Equator the air starts to rise in a fairly narrow region called the intertropical convergence zone, where intense precipitation occurs. In that zone a powerful conversion from sensible and latent heat into potential energy occurs as the air expands and the water vapor condenses, the net effect being a cooling of the equatorial atmosphere.

The upper branch of the Hadley cell now transports the air, which has become relatively cold but which has a high potential energy, into the winter hemisphere. In the rather wide downward branch in the subtropics the subsiding cold air is strongly heated by compression, and the potential energy supplied to the air in the equatorial convergence zone is converted back into heat. One would expect that the sinking air in the subtropics would be dry, since almost all the moisture was rained out in the upward branch of the Hadley cell. That expectation is confirmed by the location of the continental deserts and the small amount of rainfall over the oceans in this latitude.



CELLULAR MODEL of atmospheric circulation was first proposed by the English meteorologist George Hadley in 1735 and was modified by the American meteorologist William Ferrel in the 19th century. The pattern has a rotational symmetry around the earth's axis. The two tropical cells are called Hadley cells; two mid-latitude cells are called Ferrel cells.

The large overturning in each hemisphere of the kind Hadley envisioned is not adequate to transport enough energy poleward to counteract the externally imposed heating gradient. In such a situation temperatures near the Equator would start to rise above the observed values, and near the Pole they would start to drop. This would continue until a critical value of the north-south temperature gradient was reached, at which point zonal (east-west) asymmetries would start to develop (this process is called baroclinic instability). Theoretical models indicate that the maximum instability would tend to develop with atmospheric waves a few thousand kilometers long. In the middle latitudes, where the strong meridional temperature gradients are found, these waves can grow very fast and can take over the task of transporting energy poleward from the Hadley cell.

The familiar traveling cyclones and anticyclones, which can be found on every weather map in the middle latitudes, are a manifestation of this instability process. They form an extension of the large waves in the middle and upper troposphere. These systems mix heat in an efficient way through horizontal processes. At the same level one finds warm, humid air flowing poleward and cold, dry air flowing equatorward. On the average these flows are equivalent to a net poleward transport of sensible and latent heat. Waves with lengths of a few thousand kilometers and with time scales of a few days to a week appear to be mainly responsible for the transfers. The typical "variable" climate of middle latitudes is determined to a great extent by such large-scale waves. These waves are more intense and frequent in winter than they are in summer, since they generally develop in regions of strong horizontal temperature contrasts.

In middle and high latitudes the mean meridional circulation is weak. One can probably interpret the reverse, mid-latitude Ferrel cell as a circulation that is being driven, or forced, by the atmospheric waves. The net effect of this "indirect" cell is the sinking of relatively warm air and the rising of cold air! At high latitudes near the Pole there is some suggestion of a direct polar cell; in the Northern Hemisphere this cell is very weak. The slow rising motion between roughly 50 and 60 degrees north latitude is connected with the upward branches of the Ferrel and polar cells, and its effects are evident in the climatological records. In this belt one finds a second maximum in rainfall. The precipitation, however, occurs at irregular intervals and is mainly determined by the frequency of the weather systems passing by.

In summer the mean meridional circulation appears to be disorganized and weak at all latitudes. Asymmetries connected with the distribution of continents and oceans dominate the circulation. The land generally acts as a heat source and the colder water at middle and high latitudes as a heat sink. One apparent asymmetry is the Asian monsoon, which carries warm and humid air far north into the Asian continent. At most other longitudes in the northern part of the Tropics the air still moves equatorward. In this season studying the asymmetries in the circulation is probably more relevant than studying the mean meridional circulation, which has rotational symmetry around the earth's axis.

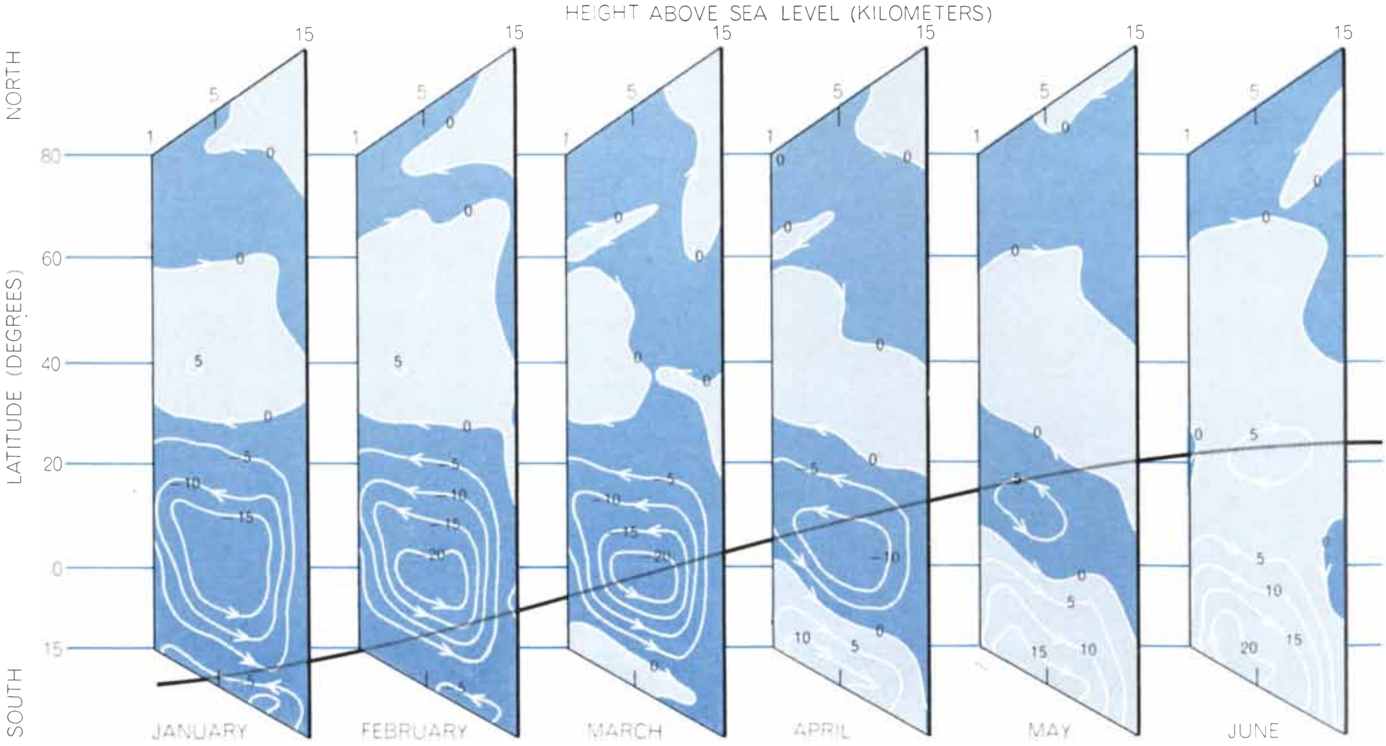
Up to this point I have discussed only some mean features of the climate as they have been derived from the observations of the past 20 to 30 years. Paleontological and even meteorological records show that the climate has changed slowly but significantly in the past and probably is changing now. On the other hand, it appears unlikely that either the total influx of solar energy or the rotation rate of the earth have changed drastically during the period in which life developed on the earth. Therefore it is probably safe to assume that the basic circulation regime has not changed. However, relatively minor changes in the strength of the north-south energy exchange, through either the mean meridional circulations at low latitudes or the large-scale horizontal waves at middle latitudes, can cause deviations from the present climate. Needless to say, any such deviations could be very significant as far as the living organisms are concerned.

The most likely way the climate could be influenced by either natural or artificial means seems to be through a trigger mechanism that ultimately changes the radiation balance. For example, if the cloud cover or dust content of the air were changed at high latitudes, the amount of reflected radiation would increase and consequently less solar radiation would be available to heat the atmosphere and the earth's surface at these latitudes. The resulting increase in the north-south heating gradient would presumably lead to more violent and more frequent disturbances in the middle latitudes. These circulations would in turn affect the original cloud cover. From that point on it seems hopeless to predict with any degree of certainty what the additional effects on the climate would be.

Changes in the reflectivity or absorptivity of the earth's surface can also alter the climate. It has been suggested that if the snow and ice fields near the North Pole were to be covered with black carbon, the Arctic Ocean might become ice-free through the increased absorption of solar radiation in summer. Again the present radiation balance and the climate over the earth would be affected. Still another possibility would be a change in the relative proportion of the atmospheric gases. For example, the measured slow increase in the carbon dioxide content of the air due to the burning of fossil fuels would presumably lead to more absorption of long-wave terrestrial radiation in the atmosphere and consequently to extra heating. One can think of many other ways in which changes in the earth's macroclimate might occur.

One must also consider the possibility of external influences such as natural variations in the amount and the spectral distribution of the incident solar radiation itself associated with variations in the level of solar activity. For instance, during periods of high solar activity the solar output mainly increases in the ultraviolet portion of the spectrum. Since most of that radiation is absorbed above 30 kilometers, one would expect to find the largest dynamic response at those levels. It is still an open question whether or not such variations in solar emission—either in the form of increased ultraviolet radiation or possibly also in the form of showers of energetic particles—affect the weather deep down in the atmosphere. The meteorological evidence for direct climatic variations caused by such changes in solar output is inconclusive, but variations of this kind certainly cannot be ruled out.

As an example one can imagine that through a change in the radiation balance the general regime of atmospheric and oceanic circulation could be brought to settle in a new quasi-equilibrium state that would be slightly different from the state it is in now. According to some recent studies conducted by M. I. Budyko in the U.S.S.R. and William D. Sellers in the U.S., even the present state of the atmosphere might not be as stable as one would like to think; these authors suggest that comparatively small changes in the present state can lead to a new ice age. Another consideration is that an initial disturbance of the circulation might, if maintained for a long enough time, ex-



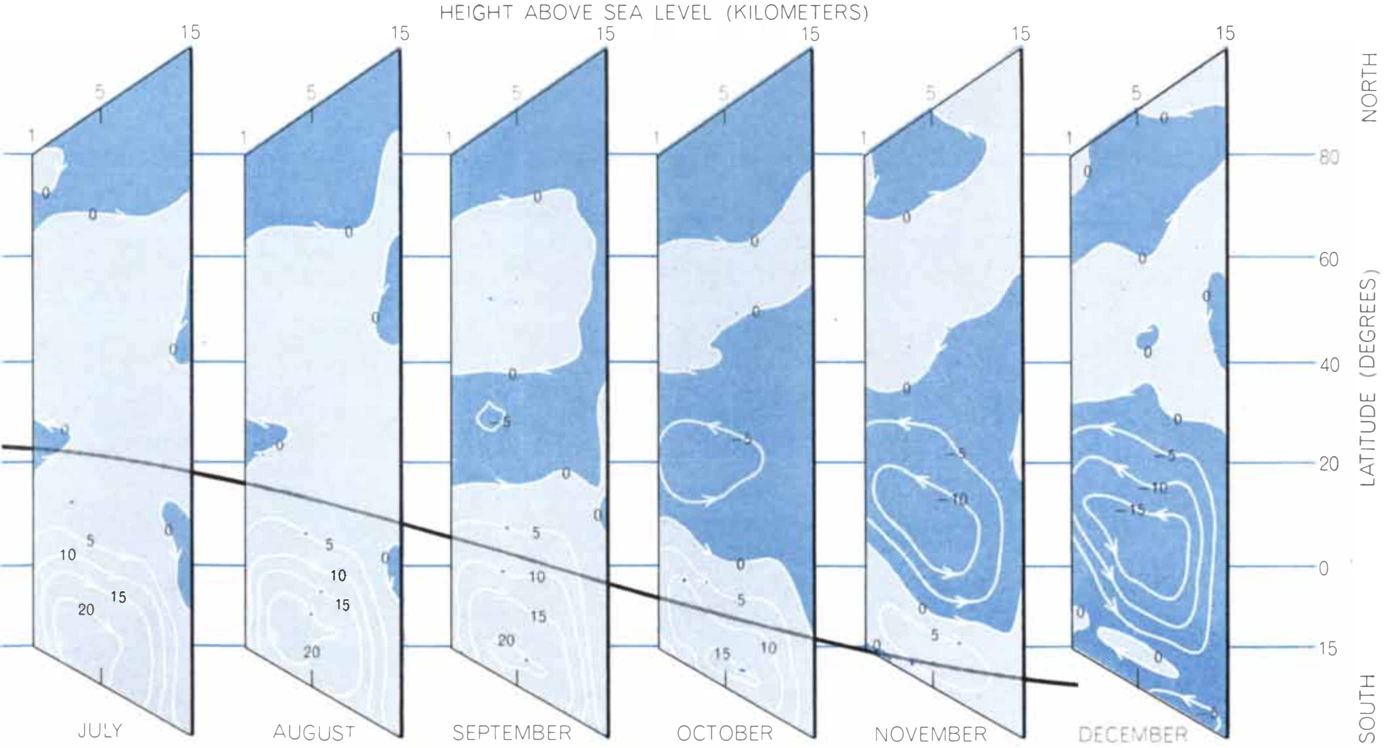
ANNUAL CYCLE in the mean meridional circulation of the Northern Hemisphere was investigated by the author and Eugene M. Rasmusson using data from an extensive radiosonde network. They found that while the Hadley cell on the winter side of the Equator grows in strength and even expands across the Equator, the summer Hadley cell tends to weaken and finally almost disappears. Thus in contrast to the Hadley-Ferrel model there appears to be little symmetry in the tropical circulation with respect to the Equator, except cite a long-term climatic fluctuation. The period of this fluctuation would probably be related to the natural turnover time of the oceans (of the order of a century or more) because of their capacity to store large amounts of heat.

Some reassurance that our present climate is not too unstable may be gained from the fact that during the past few centuries the climate has not fluctuated widely. An important complicating factor is the highly interactive nature of the different processes that operate in the ocean and the atmosphere. This makes it practically impossible to deduce through simple reasoning or even by using a simple model what would happen if one could bring about a slight, but more or less permanent, change in the radiation budget.

A high-priority task in the examination of these problems is to establish from observations how the present general circulation in both the ocean and the atmosphere is maintained. Here important contributions have been made in the past 20 years by three groups, one led by Victor P. Starr of the Massachusetts Institute of Technology, the second by Jacob Bjerknes of the University of California at Los Angeles and the third by Erik H. Palmén of the University of Helsinki. The next tasks are to determine whether or not slow changes in the general circulation are taking place, and to try to establish possible cause-and-effect relations. The limited records and the tremendous job of reducing the observations to meaningful parameters, however, severely restrict this direct approach.

With the arrival of large electronic computers a powerful new method for studying the climate has been developed. The thermal structure and the dynamics of the atmosphere are simulated through numerical integration in time of the equations that govern the behavior of the atmosphere. The basic equations are the equations of radiative energy transfer, the equations of motion and the thermodynamic equation. Starting from certain initial conditions (for example a uniform-temperature atmosphere at rest), the integration is carried out in time steps of the order of 10 minutes, and new values for the meteorological parameters (wind components, temperature, pressure and humidity) are calculated at each point in a three-dimensional grid covering the global atmosphere. The most realistic numerical experiments to date have been conducted at the Geophysical Fluid Dynamics Laboratory of the Environmental Science Services Administration by Joseph Smagorinsky, Syukuro Manabe and Kirk Bryan, Jr. In their experiments the number of grid points in space is of the order of 50,000 (about 10 vertical levels and a horizontal grid distance of about 300 kilometers). After the atmosphere has settled down and recovered from the unrealistic initial conditions, the relevant general circulation statistics are calculated in the same way they would be for the real atmosphere. With the present grid the large-scale weather systems seem to be rather well resolved.

On the other hand, the smaller-scale phenomena such as cumulus convection cannot be simulated explicitly. They have to be incorporated in a different way. In spite of these uncertainties and others (such as the lack of knowledge of how to properly incorporate the exchange processes near the earth's surface), the results so far are encouraging. Although the ability to forecast the exact location and intensity of the important weather systems degrades rather quickly in the course of a week, the predicted statistics of the average behavior taken over a much longer period appear to reproduce the observed statistics rather well. The numerical experiments seem to be the most promising road to a better understanding of the present climate. In addition they provide a powerful tool for evaluating the effects on the climate of natural or man-made disturbances.



possibly in the spring and fall. Outside the Tropics they found only a weak, indirect circulation in middle latitudes and a very weak, direct circulation near the Pole. In both middle and high latitudes asymmetric "weather" systems dominate the circulation and the mean meridional circulation is almost negligible. Contour units indicate the total mass transport of air (times 10^7 tons per second) integrated both horizontally along the latitude circle and vertically from the earth's surface up to the height of the contour.