Monsoons

By concentrating the solar energy reaching the ocean onto the land these seasonal winds bring water to half of the people of the earth. Computer simulations may soon predict their dry and rainy phases

by Peter J. Webster

If the earth were a simpler planet, capped over most of its Northern Hemisphere with a single continent and covered elsewhere with one vast ocean, the weather patterns near the coast of the continent might not be much different from those that regulate life on three of the continents of the real earth. There would be two major seasons on the coastal plain, a rainy season and a dry one. Within the rainy season periods of drenching squalls would alternate with equal periods of sunny weather every week or two. The inhabitants of the coastal areas and the southern interior of the mythical continent would become accustomed to dependable cycles of seasonal change.

In at least one important way life on the mythical planet would be quite different from life on the real earth: on the mythical planet it would be possible to forecast major weather patterns accurately. Indeed, the mythical planet is a simplified model of the earth that has been developed for the simulation of global weather patterns with the aid of a computer. On the model planet one can predict the onset of the rainy season, the alternation of dormant (dry) and active (rainy) weather within the rainy season and the approximate date of the cessation of the rains at the beginning of the dry season. A farmer on the model planet with access to such information could time his plantings and choose his crops to ensure adequate precipitation and maximize his chance of a successful harvest. For the two billion people of the real earth who depend on seasonal rains for drinking water as well as for agriculture such accurate forecasting would have a profound effect on everyday life.

The terrestrial weather patterns simulated by the model planet are monsoons. The term monsoon has most often been applied to seasonal changes on the shores of the Indian Ocean, and in particular to a wind system in the Arabian Sea that blows from the southwest during one half of the year and from the northeast during the other half. The term is thought to stem from the Arabic word *mausim*, meaning season. As the underlying mechanisms of monsoons have come to be understood, the term has come to signify any annual climatic cycle with seasonal wind reversals that generally cause wet summers and dry winters. The largest and most vigorous monsoons, however, are found in the regions of the earth where they were first named: on the continents of Asia, Australia and Africa and in the adjacent seas and oceans.

Although the definitive characteristic of the monsoon is a seasonal pattern, fluctuations are observed on time scales ranging from days to decades. The short-term variations include not only the active and dormant phases in the rainy season but also individual disturbances in the active phase. During an active phase the weather is unstable, with frequent storms that carry the deluges often associated with the monsoon. During a dormant phase the weather is dry, hot and stable, and notable for an absence of tropical storms. Over much longer periods there are variations in annual precipitation that can lead to years of drought or flood. The superannual cycles are still too poorly understood for forecasting to be practical, although years of flood or drought can be expected about 30 times per century. Recent developments in the theory of moist processes in the atmosphere, however, may soon make predictions of the active and dormant phases feasible.

Practical knowledge and the general predictability of monsoon phenomena played an important social and economic role in many ancient civilizations of the Eastern Hemisphere. Long before the arrival of Europeans, merchants had plied trade routes between ports in Asia and eastern Africa, adapting their commerce to the seasonal rhythms. In 1498 an Arab pilot showed the Portuguese explorer Vasco da Gama the trade route to India from the east coast of Africa, and the monsoon winds became the basis of a lucrative trade and cultural exchange between East and West. The European traders and adventurers returned home with fragmentary information about the southwesterly winds of summer and the northeasterly winds of winter.

Provided with such observations of low-latitude weather, European scholars were able for the first time to consider the circulation of the atmosphere on a global scale. Two of the most important early studies were done in the late 17th and early 18th centuries by Edmund Halley and George Hadley. Halley attributed the monsoon circulation primarily to the differential heating and cooling of the land and the ocean. Differential heating, he reasoned, would cause pressure differences in the atmosphere that would be equalized by winds. Hadley noted that the rotation of the earth would change the direction of such winds, causing winds moving toward the Equator to veer to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. Although more recent work has refined the understanding of the two processes, they are still considered fundamental causes of monsoon phenomena.

There is a third factor, however, that determines many of the distinctive features of the monsoons. The range of temperature and pressure over much of the surface of the earth lies near to the triple point of water. The triple point of a substance is the combination of temperature and pressure at which its solid, liquid and gas phases can coexist. For water the triple point lies at a temperature of .01 degree Celsius and a pressure of 6.104 millibars. Water molecules whose environment is near to the triple point can be freely interconverted among all three states. In contrast, carbon dioxide molecules cannot enter the liquid state at the temperatures and pressures ordinarily encountered at the earth's surface; the pressure must be raised considerably before solid carbon dioxide (dry ice) will melt instead of sublimating into its vapor phase.

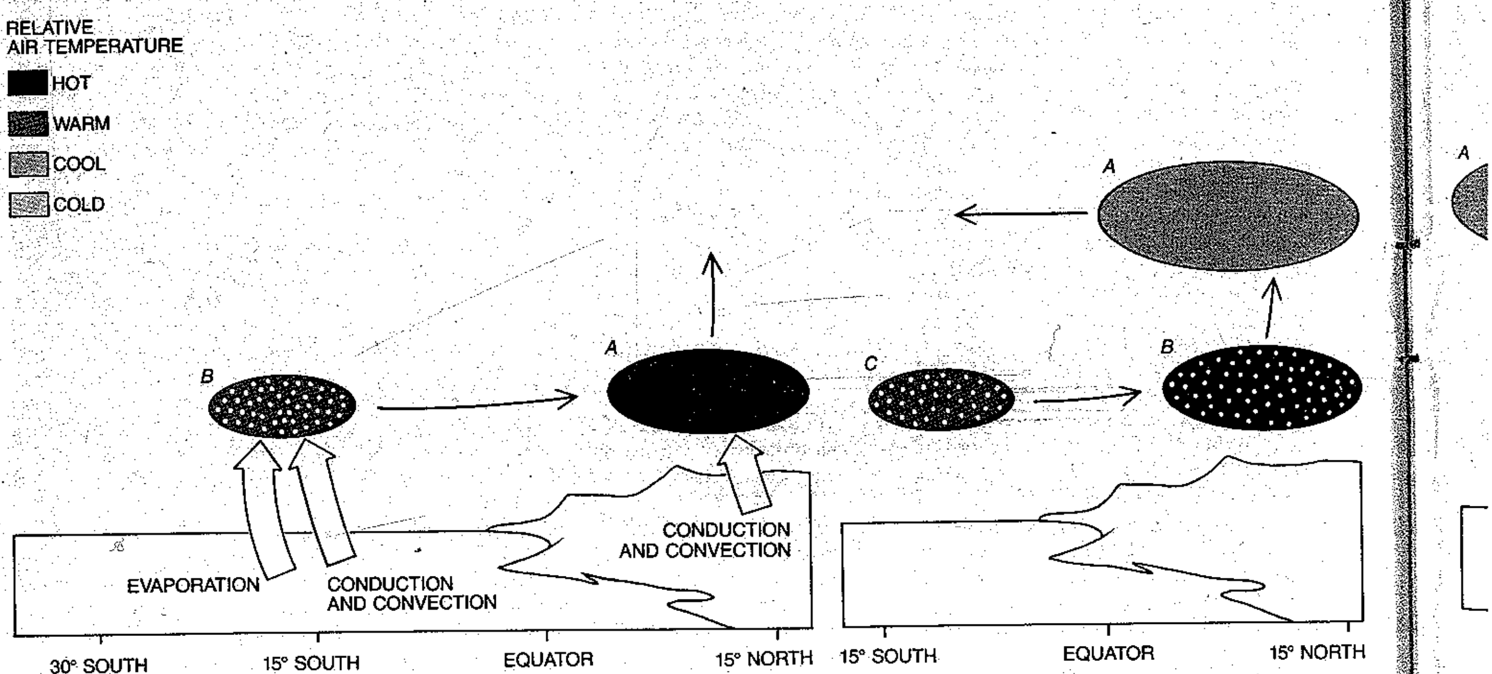
The ability of water to readily evaporate and condense in the atmosphere has a profound effect on monsoon circulation. It is primarily in understanding the effects of moist processes that modern meteorology has made its major theoretical contribution. When water changes from a solid to a liquid, energy must be supplied to break down the crystalline structure of ice so that the molecules can move about more freely in the liquid state. Similarly, energy is required in order to transform the phase from the liquid to the vapor. The energy expended to evaporate water is stored as kinetic energy of the molecules of the water vapor; when the molecules condense again, the energy is released. Thus during a phase change energy in the form of heat is added to or subtracted from a substance without changing its temperature. One can appreciate the effect by noting that although the ice in a glass of ice water will melt in a warm room, the temperature of the water does not change as long as some ice remains.

The importance of moist processes stems from the fact that the water evaporated at any given time from the world's oceans stores about a sixth of the solar energy reaching the surface of the earth. When the water condenses again and falls as rain, the energy stored in the vapor phase of the rainwater is released. In monsoon circulation part of the enormous reservoir of solar energy collected over the oceans can be released over land when the water in moist ocean air condenses over the land. It is the release of this energy that is responsible for the power and the duration of the monsoon rainy season and for the variation within the rainy season between active and dormant phases.

To understand more precisely how moist processes function in monsoon circulation it is necessary to appreciate the workings of the basic driving mechanism of the circulation, which was first discussed by Halley in 1686. The atmosphere is heated differentially because land areas tend to be warmer than the oceans in the summer but cooler in the winter. The land and the oceans respond differently to solar radiation for two reasons. One of the intrinsic properties of water is its high capacity to store heat compared with the capacity of many other substances. The specific heat of a substance is a measure of its heat capacity: the specific heat is the amount of energy that must be supplied to raise the temperature of one gram of the substance by one degree C. The specific heat of water is more than twice that of dry land, although the specific heat of land is considerably increased when the land is wet with rain. Therefore in response to the same amount of solar radiation the temperature of a given mass of dry land will increase more than twice as much as the same mass of the ocean.

The second reason for the greater heat capacity of the ocean is its efficiency in mixing heat energy to lower depths and so distributing heat throughout a large mass of water. Wind stirring at the surface of the ocean creates turbulent eddies that have the effect of conveying warm surface water to lower levels in the summer; the warm water is replaced by cool subsurface water that is heated in turn. In the winter the heat accumulated during the summer is released by the reverse process. As the surface of the water cools because of the decrease in solar radiation, the surface water sinks and is replaced by warmer water that rises from below.

Because of mixing and the high specific heat of water the temperature of the ocean surface varies less than that of the land. The oceans act as an enormous flywheel for storing heat energy, and because of the great inertia of the system the cycle of maximum and minimum surface temperatures lags about two months behind the corresponding cycle of solar heating. In the spring—the beginning of the annual cycle of the monsoon—heat energy reaching the surface of the ocean or of the land is conducted upward into the atmosphere in warm, buoyant and turbulent bubbles of air. The rate of heat transport is proportional to the temperature difference between the ground and the atmosphere. As the bubbles rise they mix with cooler air and transfer their heat to the column of air above the heated surface. This form of heating and heat transfer is called sensible heating because the heated substance must be in contact with the heat source. Sensible heating causes the initial differential heating of the atmo-



STAGES IN THE DEVELOPMENT of a summer monsoon are controlled by the interaction of moist processes with the force that drives higher-density air toward regions of lower density. As solar radiation warms the land and the ocean the overlying air is heated by conduction and expands. Because the land heats faster than the ocean the warmer air over the land rises as buoyant, turbulent bubbles and is replaced by denser ocean air. The latter carries moisture evaporated from the ocean, which stores solar energy in the form of latent heat sphere over the land and the ocean and generates the potential energy that powers the monsoon system.

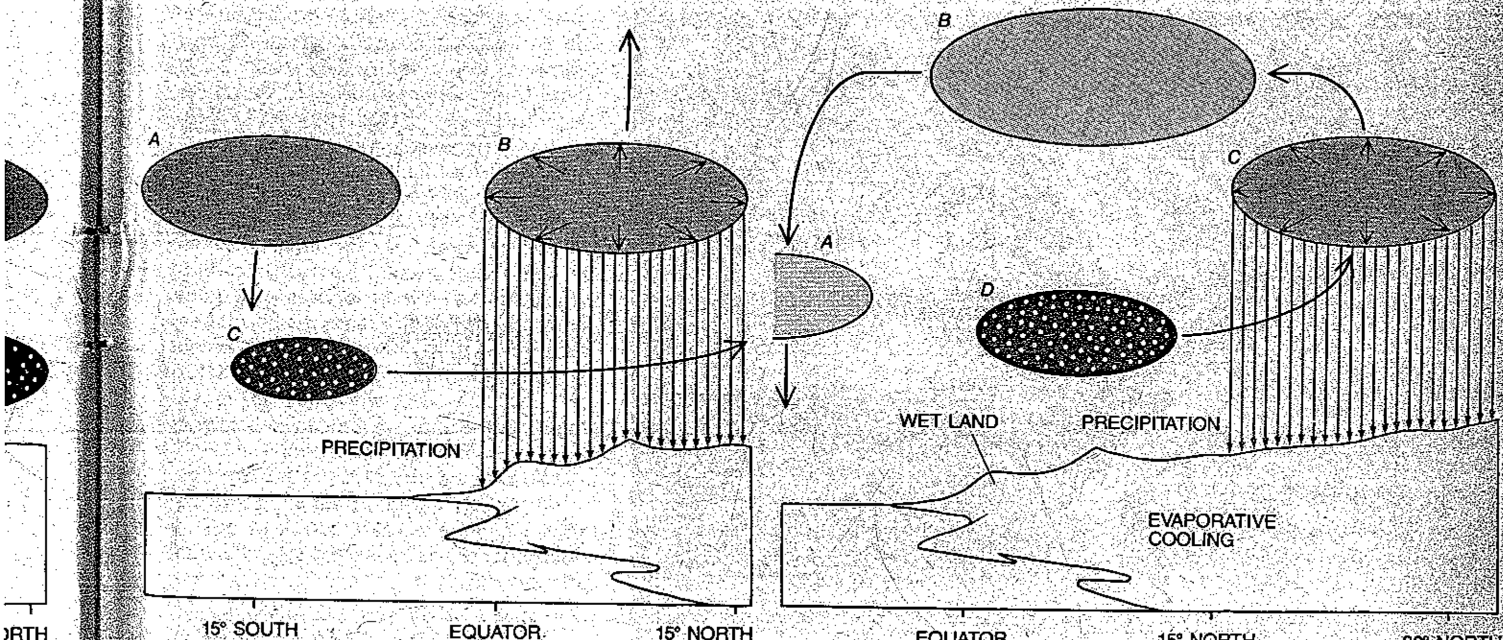
Monsoon winds are driven by the conversion of part of the potential energy of an atmospheric system into kinetic energy. The potential energy of a system under the action of gravity is proportional to the vertical distance between its center of mass and some convenient reference level, such as the surface of the earth. The potential energy can be increased by raising the center of mass of the system. This can be done either by tapping the kinetic energy of the system and thereby depleting its motion or by supplying energy from some external source. On the other hand, if the center of mass is lowered, the potential energy decreases and a corresponding amount of kinetic energy becomes available for fluid motion.

During the summer monsoon differential heating raises the potential energy of the ocean-land system by setting up a difference in pressure between parcels of air over the two regions. Because the air initially over the ocean is cool it remains denser than the air over the land. The force generated by the pressure gradient, which tends to equalize pressure differences, causes the denser, cooler air from the ocean to move toward the land and undercut the warm air over the land. The warm air is therefore forced to rise. The combined rising of the warm air and sinking of the cool air lowers the center of mass of the atmospheric system, so that the air motions release potential energy. At the same time the steady input of solar energy tends to raise the potential energy because of the continued differential heating of the land and the ocean. The winds of the monsoon are the result of the tendency of the atmosphere to minimize the pressure gradient between the land and the ocean. They can therefore be understood from an energy standpoint as the result of the conversion of solar energy into potential energy and then from potential energy into kinetic energy.

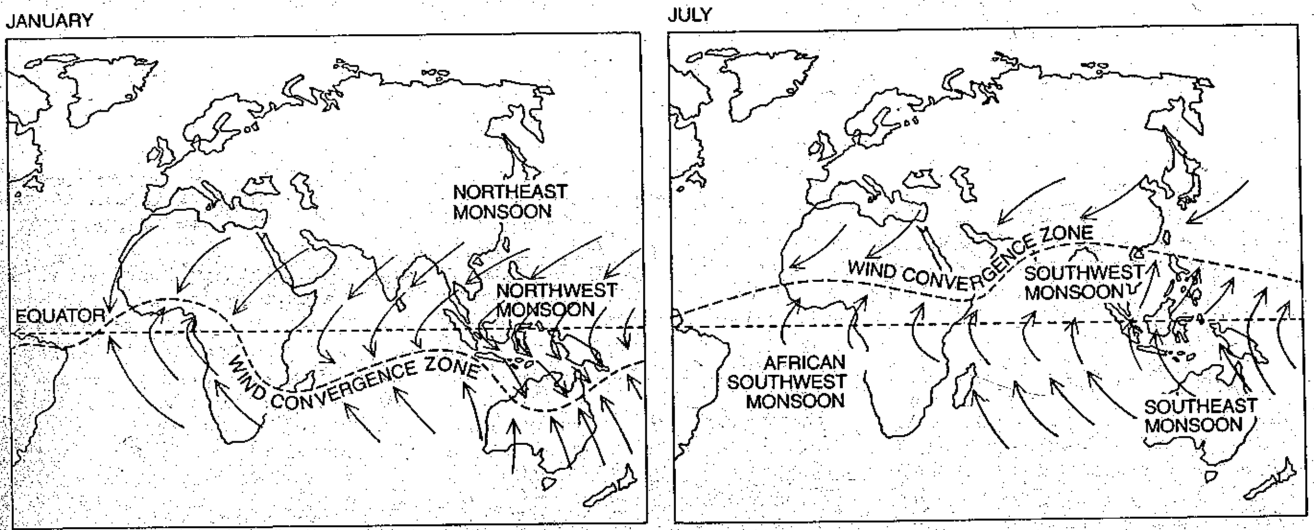
The circulation of the monsoon winds is deflected by the rotation of the earth through the action of the noninertial force known as the Coriolis force. The deflection distinguishes monsoon winds from diurnal sea breezes, which also stem from differential heating. The latter arise and diminish too quickly to be much affected by the Coriolis force. Hadley's description of the Coriolis force is sufficient for winds moving from the poles of the earth to the Equator, but the general effect can be succinctly described for winds moving in any direction. The Coriolis force deflects winds to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. The magnitude of the deflection depends on the latitude of the wind motion: the deflection is maximum at the poles and zero at the Equator. It is directly proportional to the trigonometric sine of the latitude.

The summer monsoon will ideally continue in a steady state until the balance between the potential energy generated by solar radiation and the release of the potential energy by the atmospheric system is upset. In Asia, for example, solar heating diminishes substantially after the autumnal equinox and the temperature of the adjacent oceans starts to fall. Simultaneously regions in the Southern Hemisphere, particularly over the Indonesian archipelago, become the centers of maximum heating. As the temperature difference between the Asian land masses and the surrounding oceans decreases, the potential energy of the system runs down. The monsoon is said to retreat and the winter dry season begins in the Northern Hemisphere.

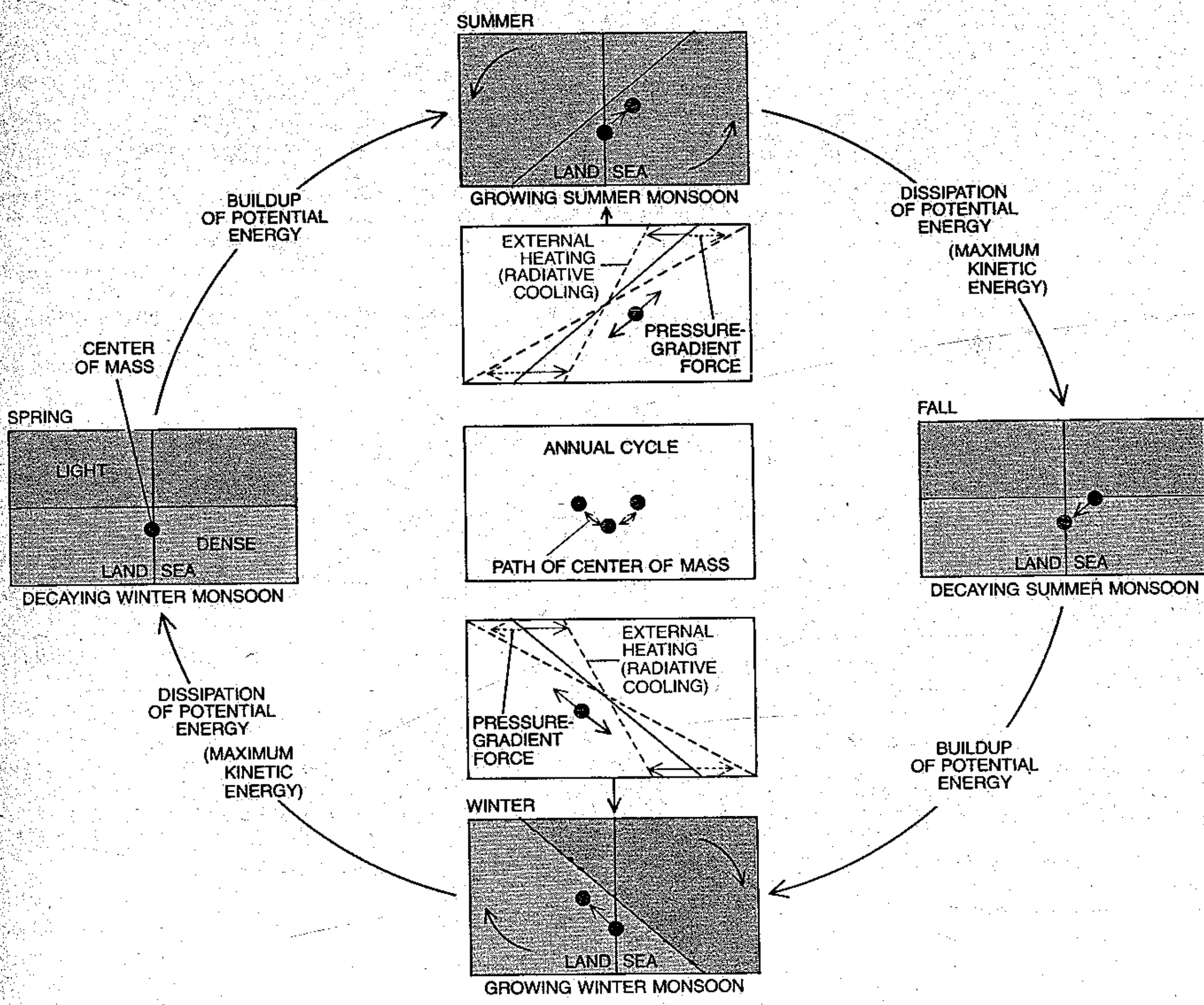
With the onset of winter both the land and the oceans of the Northern Hemisphere lose heat by radiation to space. The radiative losses are attenuated by clouds, but the cloud cover is usually less extensive over the land than it is over the ocean. The resulting increased heat loss from the land and the greater heat capacity of the ocean restore the temperature differences to the system and raise the potential energy once again. Cold, high-pressure air over northern Asia moves toward the Equator in order to restore equilibrium and is deflected to the right by the Coriolis force. The cold air mass, moving from the northeast along the surface, is balanced by warm air from the south that moves northward in the upper troposphere. The rotation of the earth deflects



(*colored stipple*). When the moist air moves inland, it too rises and its water vapor condenses, releasing latent heat. The additional heat causes the air to expand and rise further, reducing the pressure in its wake and so intensifying the monsoon airflow. Rainfall cools the land because evaporation of the water absorbs a portion of the incoming solar radiation. Hence the region of maximum ground heating moves inland and the region of maximum precipitation follows. Air pressure from dense to light is shown by relative sizes of the air parcels.



SEASONAL WIND REVERSAL is characteristic of monsoon circulation throughout the world, but it is most pronounced in the regions around the Indian Ocean. Note that in crossing the Equator the winds change direction, an effect of the rotation of the earth. The zone where the surface winds converge is primarily in the Southern Hemisphere in January but migrates northward with the sun in July.



TEMPERATURE DIFFERENCE between the air over the land and the air over the ocean raises the center of mass of the atmospheric system and so increases its potential energy. The temperature difference is maintained by external heating in the summer and by radiative cooling in the winter. The flow of air caused by the pressure gradient between the two air masses tends to decrease the potential energy of the system and to increase its kinetic energy. Monsoon circulation results from the balance between the two effects. When the monsoon is in equilibrium (summer and winter), the gain of potential energy by external heating or radiative cooling exactly equals the loss caused by the action of the pressure-gradient force. In fall and spring the center of mass falls and the potential energy of the system is dissipated.

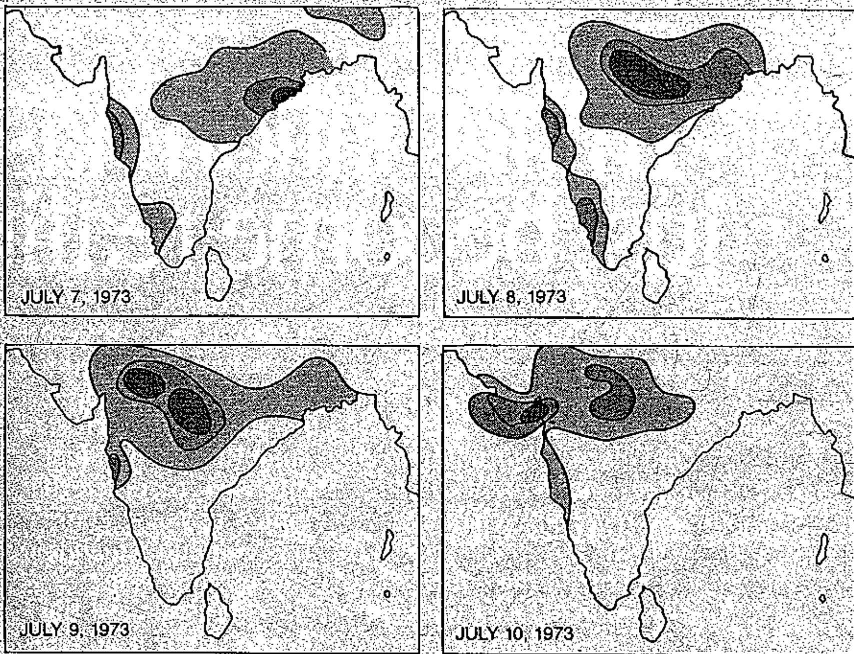
the warm upper air to the east, creating an intense jet stream over Asia and Japan in which speeds commonly reach 100 meters per second, or more than 200 miles per hour. The jet-stream flow often becomes unstable over the central north Pacific and spawns the low-pressure winter storms prevalent in the middle and high latitudes of the Western Hemisphere.

The northeast monsoon of the winter continues in a steady state much like the southwest monsoon of the summer, until solar heating in the spring dissipates the potential energy that powers the winter monsoon. As the temperature of the land again overtakes the surface temperature of the ocean, the potential energy builds up and the cycle begins once more.

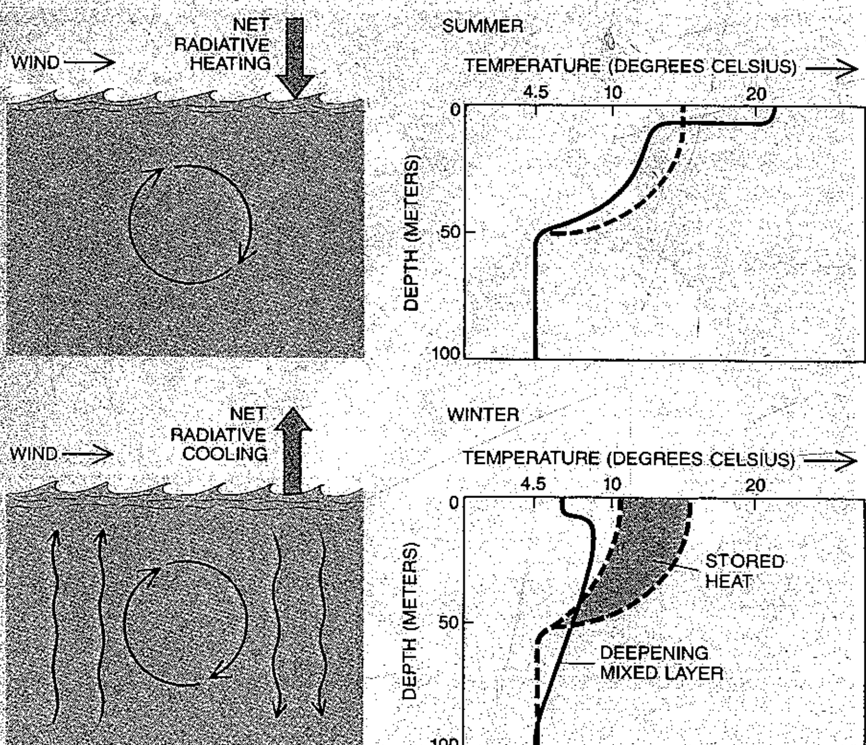
What role do moist processes play in the annual circulation? During the summer monsoon water vapor evaporated from the ocean is borne along with the air moving toward the land. If a parcel of air is displaced vertically in such a way that heat energy neither leaves it nor enters it, the temperature and pressure of the parcel undergo what is called adiabatic change. If the parcel rises, it moves into a region of lower pressure. A pressure gradient then exists between the air parcel and its new environment; in order to equalize the pressures the parcel tends to expand. To expand, however, the parcel must do work on its environment at the expense of the kinetic energy of its molecules. Reducing the kinetic energy of the molecules entails reducing the temperature. If there is no heat exchange across the boundaries of the parcel, the process is called adiabatic cooling. Conversely, in adiabatic heating the temperature of a subsiding air parcel increases as the parcel is compressed by its environment, even though no heat energy is added to (or subtracted from) the parcel.

An air parcel carrying moisture from the sea is warmed by conduction and by upward-moving convective air currents over the land, and it begins to rise to higher altitudes of lower pressure. As the parcel ascends it cools adiabatically and the water vapor condenses into raindrops. In the course of condensation the solar energy that has maintained the water in the vapor phase is released. The released heat energy, called the latent heat, is taken up by the air molecules and thereby causes a nonadiabatic temperature change in the air parcel.

The heat liberated in this way adds considerable buoyancy to the rising column of air over a warm continent. The air parcel rises still higher, further reducing the pressure over the land and bringing on a more vigorous influx of moist air from the ocean. Hence one effect of moist processes in the atmosphere is to increase the strength of



DISTURBANCES during an active phase of the summer monsoon come about because of shear, or variations from place to place in the horizontal speed of the wind. Shear regions often become unstable and spin off the main stream of air just as turbulent eddies spin off the main current of a river. Such a disturbance can intensify with the release of latent heat into an area of precipitation extending for hundreds of miles. Progress of disturbance can be followed by mapping the daily accumulation of rainfall over a period of several days.



SOLAR HEAT reaching the surface of the ocean during the summer is distributed throughout a layer about 50 meters thick as a result of turbulence induced by the wind. In the winter the cycle is reversed and the cool surface water is driven down by the wind and by its own greater density. It is replaced by the warmer, less dense water that accumulated below the surface the preceding summer. Broken lines represent the average distribution of heat energy as a function of depth. Mixing is the chief reason the ocean temperature lags behind the solar cycle.

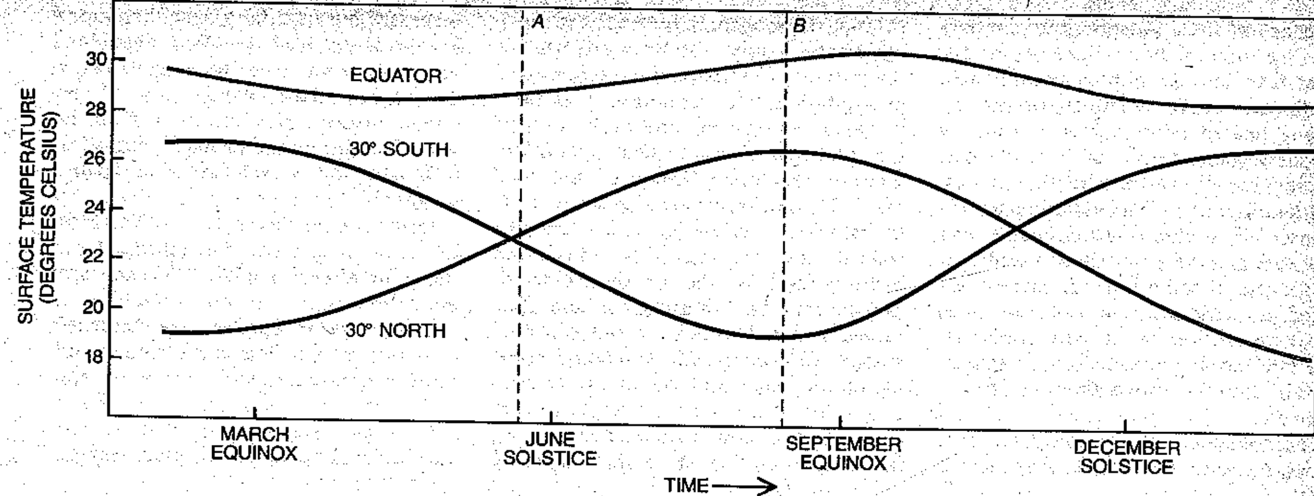
the monsoon circulation. Without moist processes the circulation would still exist, but it would be weaker.

Because of the rising column of air, temperatures in the upper troposphere over southern Asia are much warmer in the subtropics than they are over the Equator. The result is a pressure-gradient force toward the Equator at high levels, the opposite of the force near the surface. The rotation of the earth deflects the upper-level flow westward into an intense east-to-west jet stream in which winds may reach speeds of 50 meters per second, or more than 100 miles per hour. The jet stream extends across the Indian Ocean and Africa, where it crosses the Equator and merges with the winter westerlies of the Southern Hemisphere. The winds finally subside over the subtropical high-pressure belt formed during the winter in the Southern Hemisphere. The general features of the upper-air return flow were predicted by Halley solely on the basis of rational deduction.

The influence of moist processes is most apparent in the effects of such processes on the timing of the events that make up the seasonal monsoon. Moist processes virtually define the time of its onset; they appear to determine its maximum intensity, and they control its retreat. The onset of the period of precipitation comes rather abruptly a few weeks before the summer solstice. The circulation does not reach maximum intensity, however, until from eight to 10 weeks after the solstice.

The reason for the delay is that the average precipitation on a land mass is directly related to the temperature of the ocean upwind from the land. The higher the surface temperature of the ocean is, the higher the temperature of the air over the surface is and the more water vapor the air can carry. When air from the ocean carries more water vapor, more energy is available for release when the water condenses over the land. Hence the intensity of the monsoon circulation increases. Because the oceans in the summer hemisphere reach their maximum temperature some two months after the summer solstice the vapor content of the monsoon winds does not reach its maximum value until middle or late August in the Northern Hemisphere and late February or early March in the Southern Hemisphere.

The retreat of a monsoon is the gradual cessation of precipitation sometime after the autumnal equinox. Not only is the differential heating between the oceans and the continents reduced, but so also is the energy pumped into the system by the transport of water vapor. The cooler air over the ocean holds less water vapor, so that the latent heat released by precipitation over the land gradually decreases.

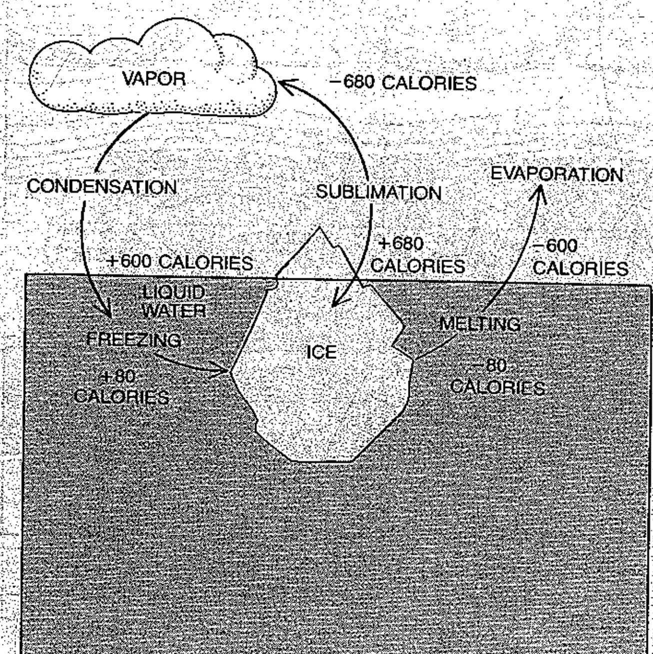


MAXIMUM AND MINIMUM surface temperatures of the ocean do not coincide with the extremes of the solar cycle. Instead they lag behind the sun by from eight to 10 weeks. Because the potential energy of the monsoon system is roughly determined by the difference in temperature between the Northern and the Southern hemispheres, the potential energy reaches a maximum about two months after the solstices and a minimum about two months after the equinoxes. The maximum ocean temperature also determines the maximum rate of evaporation, so that at the time of greatest potential energy moist processes are also most pronounced. Monsoons are most intense then.

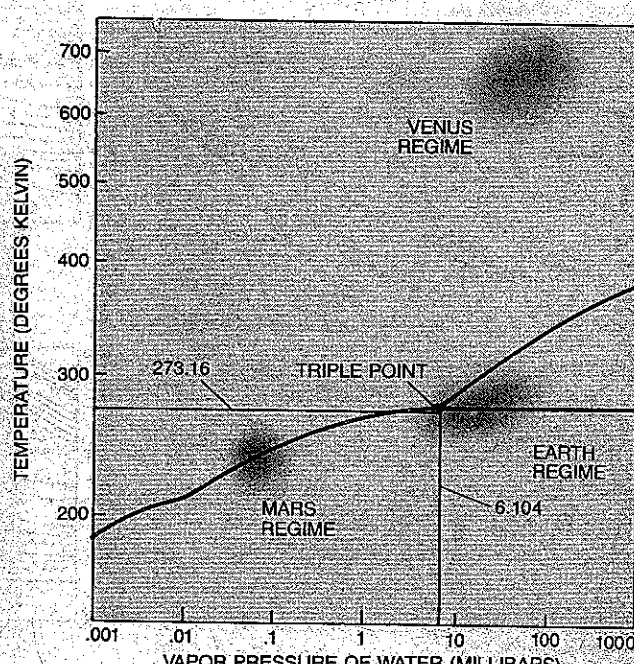
It is now possible to outline the theory of moist processes on which the computer model of monsoon circulation is based. Recall that the model planet is covered by an ocean except for a single continent that symmetrically caps the Northern Hemisphere. The coastline of the continent coincides with the parallel of latitude at 14 degrees north. In other major respects the model planet is identical with the earth: it lies the same distance from the sun, it rotates about the same inclined axis with the same period and its atmosphere is physically and chemically like that of the earth.

In the model it is assumed that the atmosphere responds to a nonadiabatic temperature change in a parcel of air by restoring the temperature of the parcel adiabatically to its original value. The assumption closely matches the behavior of the real tropical atmosphere. For example, when heat is added nonadiabatically to a parcel of air by conduction or as a result of the condensation of water vapor, the air rises to a region of lower pressure and cools adiabatically. On the other hand, if the parcel loses heat through radiation (a nonadiabatic process), the air sinks and contracts adiabatically until its temperature returns to its former value.

To simulate more realistically the



EXTERNAL SOURCE OF HEAT is required in order to change the phase of water from solid to liquid or from liquid to vapor, but because energy is conserved the heat energy is stored as latent heat in the higher-temperature phase. In a phase transition from vapor to liquid, from vapor to solid or from liquid to solid the stored energy is released. The temperature of a substance remains constant during a change of phase even though heat energy is exchanged in the process.

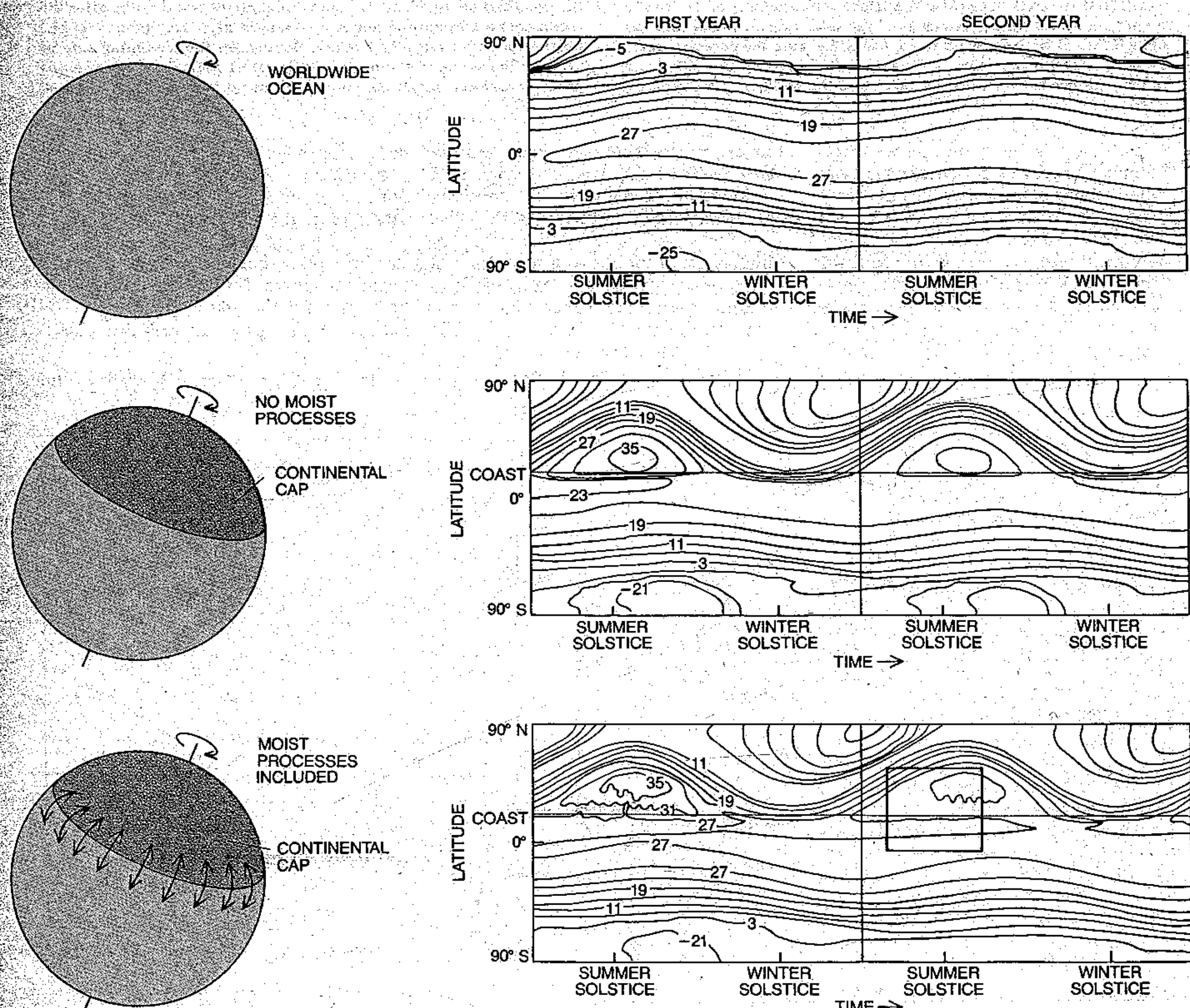


TRIPLE POINT OF WATER is the unique combination of temperature and pressure at which the solid, liquid and vapor phases of water can coexist. Of all the planets only the earth maintains conditions close to the triple point. Water whose environment is near to the triple point can be freely interconverted among the three phases. For this reason solar energy can be collected and stored in a higher-energy phase, then transported and released over a relatively small region.

tendency of the atmosphere to compensate for nonadiabatic heat input one must take into account a complicated nonlinear system. Vertical air motion over a heated continent is a result of interdependent forms of nonadiabatic heating, chiefly sensible heating and latent heating, as well as the adiabatic response. When precipitation begins over land, the ground is moistened and part of the solar radiation previously engaged in heating the surface is diverted into evaporation of the soil moisture. The land cools and sensible heating of the air directly above the wet land is reduced.

The reduction of sensible heat does not significantly alter the driving mechanism of the monsoon, because the sensible heat is only about one-tenth the magnitude of the latent heat released in precipitation. The reduction does have the effect of shifting the maximum of the total heat (sensible heat plus latent heat) toward the interior of the land mass. The region where the vertical velocity of the circulation is at its maximum follows the shift of the maximum heating, and so the condensation of moisture in the air moves inland. The monsoon cell leaves in its wake a land surface saturated with water and a relatively dry subsiding air mass. The accumulated ground water slowly evaporates and the temperature of the drying land begins to rise. As sensible heating increases over the land near the coast a low-pressure area develops again and the moist winds from the ocean are deflected from their inland course. A second monsoon cell overwhelms the inland circulation and precipitation again falls near the coast. The cycle is then repeated.

In the model the vertical wind velocity over an area of the continent can show the alternation of active and dormant phases of the monsoon. The ascending regions represent the disturbed, or active, phase. The wake, where subsidence dominates and storms are suppressed, is the dormant phase. If one examines the distribution of temperature and vertical wind velocity for several



COMPUTER SIMULATIONS of monsoon processes on three simplified models of the earth show how surface temperature (*contour lines*) varies with time and with latitude. On a model of the earth covered entirely by an ocean the surface temperature changes quite slowly with time. When the model planet is capped with a single continent and moist processes are not included in the simulation, the ocean temperature lags many weeks behind the temperature on land. The maximum land temperature lies just north of the coast. When moist processes are simulated, the land is cooled just north of the coast and the surface temperature varies cyclically during the summer monsoon. Such terrestrial features as the distance from the sun, the inclination of the earth's axis and the composition of the atmosphere are assumed to be the same in the model as they are on the real earth. The simulation can also show how vertical wind velocity can vary with time and latitude (not shown). In the atmosphere the vertical wind velocity is about a thousandth of the horizontal wind velocity.

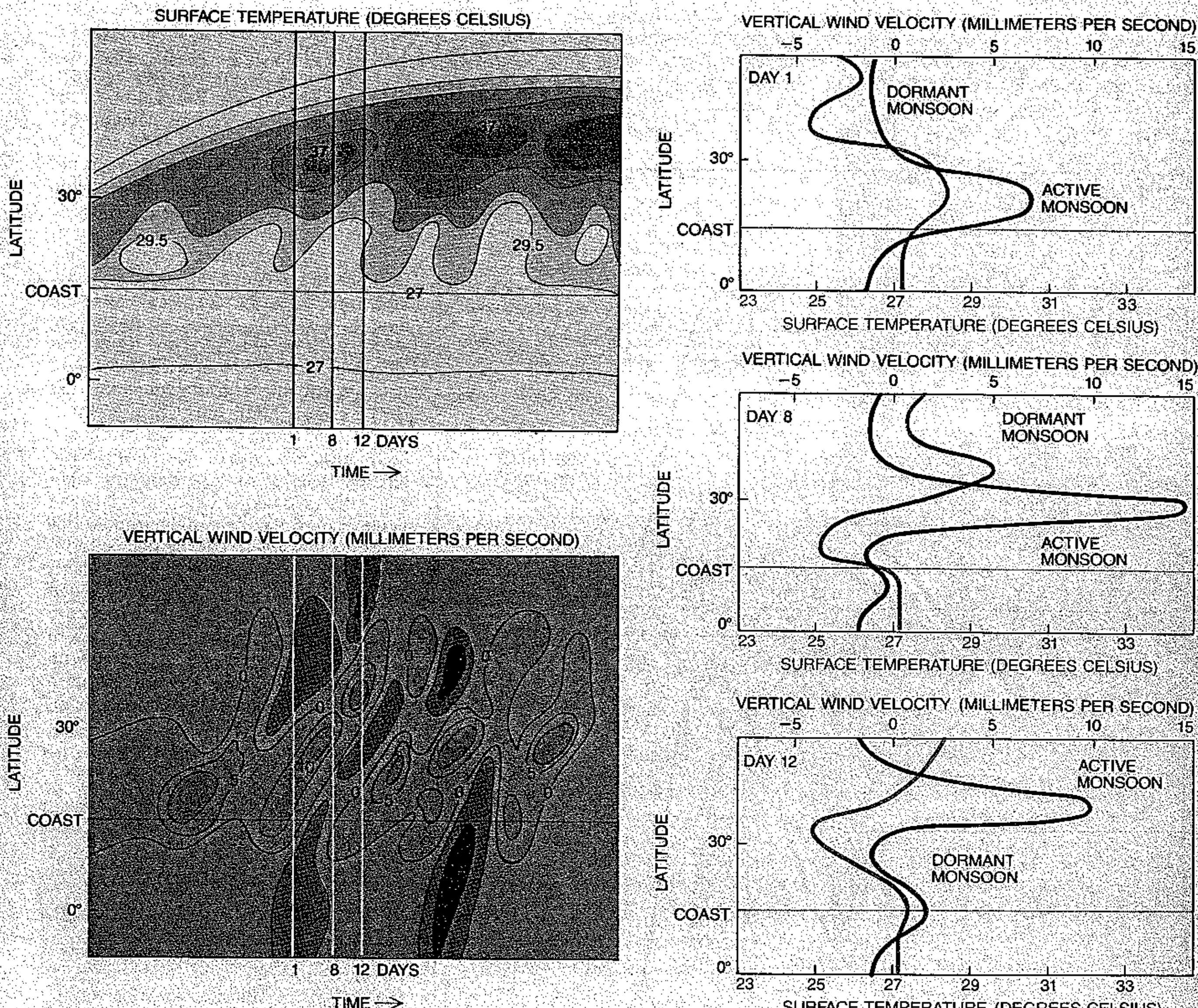
days, one can see how an active phase of the monsoon moves inland from the coast and is followed by a dormant period [*see illustration below*].

Satellite observations provide some justification for the theory of the active and the dormant phases of the monsoon that is incorporated in the mathematical model. The locus of maximum cloudiness over the Indian Ocean can be seen to move gradually northward as a monsoon cell progresses. Associated with the band of clouds are the active monsoon disturbances and intense precipitation. In the cloudless region behind the band and over most of India is a break in the active phase that heralds a period of high temperature but no rain. The cycle is observed to have a period of from 15 to 20 days, in rough agreement with the predictions of the model.

There are three separate forecasting problems that match the three time scales of monsoon phenomena. For the briefest events, such as individual disturbances in the active phase, mathematical analogues of the physical weather system can be devised. When data describing the current weather conditions are supplied, a computer simulation can extrapolate the data forward in time according to the rules of the mathematical analogue. Numerical weather prediction of this kind is an established technique that can attain reasonably good accuracy a few days in advance.

The major drawback of the method is that the initial data must constitute a complete description of the state of the atmosphere in a given region, including the variables that characterize moist processes. The collection of such data is probably beyond the capabilities of the present observational network. Remote sensing of the atmosphere by satellites and floating buoys, working in conjunction with the network of ground stations, may someday provide adequate data for forecasting.

For predicting seasonal or annual trends mathematical analogues are of little use. Here too the data are too sparse, but, more important, the compu-

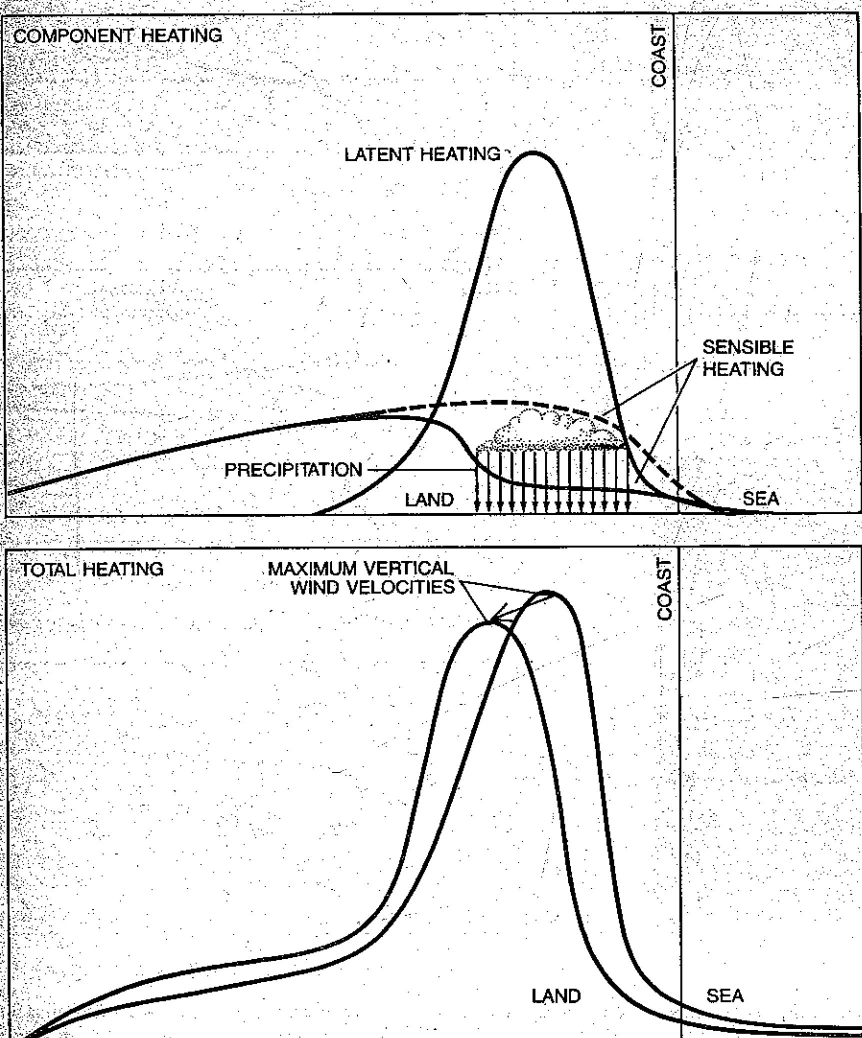


ACTIVE AND DORMANT PHASES of the summer monsoon arise in the mathematical simulation when moist processes are included in the model of the earth with a continental cap. The distribution of surface temperature with time and latitude is an enlargement of the area outlined in color in the bottom diagram on the opposite page. The distribution of vertical wind velocity is also shown. Rising air currents (*colored region*) are characteristic of the active monsoon, whereas subsiding air (*gray region*) suppresses storms and corresponds to the dormant monsoon. In the diagrams at the right the distribution of temperature and vertical wind velocity is shown in cross section for three days in the cycle. To emphasize the passage of the active and dormant phases the graph of temperature changes shows the difference between the actual temperature and the average temperature for that latitude over a 30-day period. The temperature falls in the wake of the active monsoon on days eight and 12 and rises near the coast on day 12 as the ground dries. The active cycle begins again.

tations are much too cumbersome to allow exact numerical climate forecasting. Nevertheless, the study of long series of data indicates that certain climatic developments are related to certain precursor events. For example, the winter climate of North America seems to be related to anomalies in the temperature distribution at the surface of the North Pacific. Because of the importance of moist processes to monsoons, it may be worthwhile to seek similar correlations, say between extreme monsoon phenomena and abnormal sea-surface temperatures.

It is in the prediction of the events of intermediate time scale, namely the active and the dormant phases of the monsoons, that forecasting would probably have its greatest social and economic impact. Predicting the transition from one phase to another requires a forecast for a period of weeks, too long for exhaustive numerical techniques. If the theories of the alternation of active and dormant phases are correct, however, the difficulty may be overcome. It may be possible to develop a simpler but still effective mathematical analogue that ignores events on a shorter time scale and focuses on the more slowly varying elements of the system.

Within the context of the general theory of monsoon circulation there are local and continental variations that must be taken into account. The Himalaya-Tibetan plateau, for example, appears to accelerate the onset of the Asian monsoon and to increase its ultimate intensity. Satellite data indicate that the central and southeastern parts of Tibet remain free of snow throughout most of the year. Hence the plateau must heat rapidly during the spring in the Northern Hemisphere. The precise way in which the plateau then influences the atmosphere is still unclear and has been the subject of a number of theoretical studies.



TOTAL HEATING of a column of air over the land is the sum of three contributions: radiative heating (not shown), sensible heating (from the sun-warmed land) and latent heating (from the condensation of water vapor). Precipitation tends to reduce the sensible heating of the column, causing the maximum total heating to shift inland. The region where the ascending air has its maximum velocity also shifts inland and a slow migration of the active monsoon ensues.

In contrast, the summer monsoons of Australia and Africa tend to be considerably weaker than their Asian counterparts. Over northern Australia precipitation decreases rapidly inland, so that only a narrow region along the northern coast receives significant monsoon rainfall. Similarly, the central arid lands of the African Sahel receive only spasmodic rainfall during the summer. West Africa and Australia are geographically alike as monsoon regions, and neither one is influenced by a dominant mountainous structure comparable to the Himalayas.

It may seem puzzling that there is no major monsoon system in the Americas. The equatorial region of the Western Hemisphere is dominated by the Amazon basin, whose overlying air mass is subject to sensible and latent heating for much of the year. In North America radiative cooling in the winter generates considerable potential energy between the two hemispheres. But a flow of air between them still cannot develop because it is blocked by the Andes.

The Coriolis force causes the cold North American air to enter the Pacific Ocean as the northeast trade winds. If the mountainous barrier of the Andes did not limit circulation, differential surface heating between the Amazon basin and the Pacific Ocean would cause a flow of air into the Amazon, leaving a low-pressure area over the South Pacific. Such a low-pressure area would cause the northeast trade winds to cross the Equator, and the Coriolis force would turn them toward the southeast, completing the path of interhemispheric airflow. Because of the mountains, however, the cross-equatorial flow is weak in the eastern Pacific and the trade winds continue instead across the Pacific to Indonesia. Furthermore, the eastern Pacific is dominated by cold water. Even if the Andes did not exist, the moisture content of the air would be too low to build up the high energy associated with the Asian monsoons. Air circulating in the Amazon basin is moistened by evaporation from the Atlantic Ocean.

A number of international field experiments have been undertaken to provide detailed data for research on monsoons. The most important of these were the International Indian Ocean Experiment that was conducted between 1959 and 1965 and the Monsoon Experiments (MONEX) of 1978 and 1979. The latter were part of the Global Weather Experiment, and it included separate studies of the summer and the winter monsoon circulation. In each experiment satellites, ships and research aircraft were employed in order to obtain a three-dimensional picture of an evolving monsoon. One of the most important applications of the data will be in testing theories of the monsoon's active and dormant phases.