Climates on a Rotating Earth

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The distribution of the world's climates is too regular to be due to accidents of history. The world's deserts are mostly at 30°N or S latitude and usually on the west sides of continents. Just farther toward the poles on these west sides of continents we come upon "Mediterranean climates" and farther poleward yet, the heavy rainfall, especially in the winter, that causes the temperate rain forests of Washington and southern Chile. The equatorial regions are usually wet by frequent thunderstorms of short duration. These, and innumerable other patterns, suggest that we can understand the climate as a consequence of the earth's geography, particularly its rotation. The understanding of these relations is our goal in this first chapter.

Temperature

Our heat comes from the sun, and every point on the earth gets the same amount ($\frac{1}{2}$ year) of daylight each year (because, by symmetry, for each day longer than 12 hours in the summer there is a corresponding winter day that is shorter by the same amount). But the fact that two places have the same number of hours of daylight does not mean that they get the same amount of heat from the sun. Imagine a beam of light 1 inch in diameter, carrying energy, and striking a portion of the earth's surface that is perpendicular to the beam: the energy of the beam will be distributed over 1 inch of the earth. The same beam 1 inch in diameter striking at higher latitude will be spread over a greater area of the earth and so will give less heat per unit of area (see Figs. 1-1 and 1-2). Thus, as we all know, it not only averages hotter at the equator than at the poles but is also more uniformly hot, whereas the poles have a dark, very cold winter followed by a light, relatively warm summer. This requires no further elaboration.

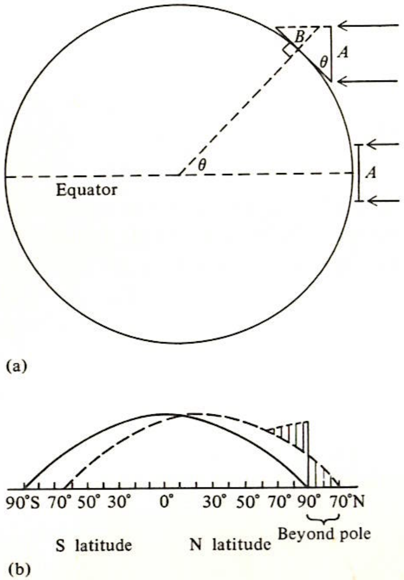

Fig. 1-1

(a) Two parallel beams of light as might come from the sun on the equinox (sun over equator). At latitude $\theta°$, the same amount of incident light falls on area $B = \dfrac{A}{\cos\theta}$. Since the intensity of light is the total radiation per unit area, it is proportional to the cosine of the latitude. (b) Intensity of light falling on the outer part of the earth's atmosphere at different latitudes. The solid line is at equinox, the dashed line at the summer solstice, June 21, when the sun is at 23°N latitude. Notice how the dashed curve folds back at the poles because the sun reaches 23° beyond the pole. The shaded areas are equal.

There is, however, an aspect of temperature that is not so obvious—the cooling with higher elevations. Why are tropical mountain tops as cool as temperate or even polar regions? Qualitatively the answer is quite simple. A parcel of air rising up a mountainside expands, like all its neighboring parcels, with the rarefied atmosphere. It does some work—uses some energy—in expanding, pushing the neighboring parcels aside and as all neighboring parcels are doing exactly the same, the energy cannot have come from them; it must have come from the parcel's own

supply of energy, which is heat. In other words, the parcel must cool. The consequent rate of cooling, which we call the adiabatic lapse rate, is 5.5°F/1000 ft, or 10°C/km. "Adiabatic" means no external source of energy was involved. But not all lapse rates are *dry* adiabatic. If the air is condensing moisture as it cools, it gains some heat of condensation, which partially counteracts the cooling. Hence the "moist adiabatic" lapse rate (about 3°F/1000 ft, or 6°C/km) is less than the dry rate. Desert mountains cool faster with elevation than mountains in moist climates; and as the air on a mountainside cools enough to condense, the lapse rate changes from dry to moist. Figure 1-3 shows, for example, a mountain with air cooling at the dry rate as it begins ascending; at about 1 kilometer, when it is cool enough for moisture to condense, it changes to the wet rate. Often, on the lee side of a mountain there is no remaining moisture, so the descending air warms at the dry rate, leaving the valley air warmer on the lee than on the windward side. The derivation of the adiabatic lapse

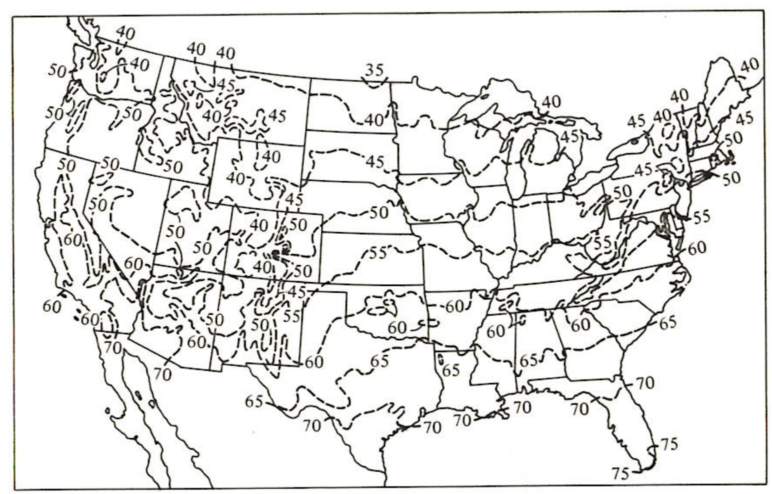

Fig. 1-2

Mean annual temperatures in degrees Fahrenheit in the United States (period, 1899–1938). From the 70° isotherm in Texas north to the 35° isotherm in North Dakota is about 1200 miles: just over 34 miles north per degree temperature rise. (From U.S. Department of Agriculture, 1941.)

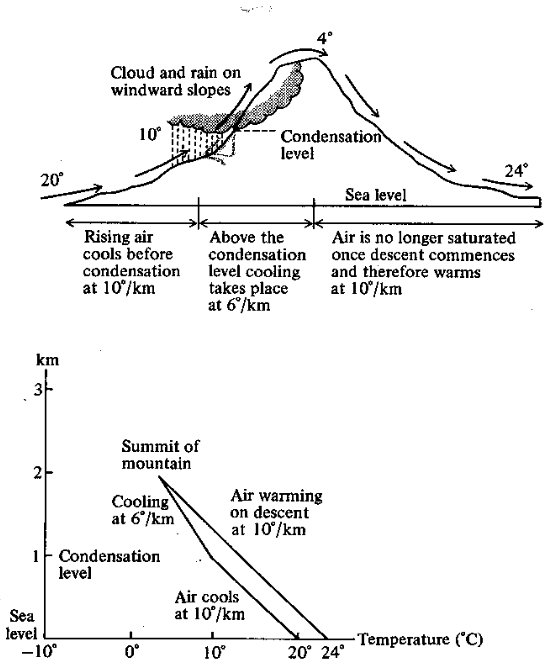

Fig. 1-3

Diagrammatic representation of temperature changes and the related climatic changes produced on the windward and leeward sides of a mountain. (From Flohn, 1969.)

rate* is simple, using the first law of thermodynamics, the ideal gas law, and the rate of pressure change with elevation. But since each of these has its own empirical constants, it is no greater burden simply to assume the lapse rate as an empirical rule. The derivation does show, however, that the cooling rate is approximately constant; that is, in going from 14,000 to 15,000 feet the air cools by about as much as going from 8000 to 9000 feet, and so on.

We now see why mountaintops are cooler than lower elevations. In fact, the 3°F cooling of 1000 feet of elevation on a moist

* See appendix to the chapter.

mountain is very roughly equal to the cooling of 100 miles of latitude, which has been called "Hopkin's bioclimatic law" (recall Fig. 1-2). But there is another lesson to be learned from the adiabatic lapse rate. We might say that under "normal" conditions the air cools at the adiabatic lapse rate as we go up in elevation. But we have all heard of "temperature inversions" and other abnormal temperature changes. Let us compare one of these with the normal adiabatic lapse rate, as we do in Fig. 1-4.

The basic picture is very simple: If heavy air is on top of light air, the heavy air will tend to sink through, hence heavy over light air is "unstable." Conversely, light air over heavy air is "stable," and light upper air is likely to stay in place.

We picture an atmosphere that has a nonadiabatic lapse rate for some reason, and first we consider one that cools faster than adiabatic with elevation. Now we suppose there is a small parcel of air being lifted by turbulence and cooling adiabatically of course as it rises. This air finds itself less cool than the neighboring air at each elevation and hence it is lighter and continues to rise, sucking up air behind it. Thus air cooling at a lapse rate faster than adiabatic is vulnerable to turbulent eddies of adiabatic air and is called "unstable." An atmosphere that cools more slowly than adiabatic with elevation is different. In this atmosphere a small eddy of rising air cooling adiabatically would be cooler and denser than surrounding air and hence would sink back down. Thus air which cools at a slower rate than adiabatic is "stable" and not vulnerable to eddies and other disturbances. Air that is warmer above than below is even more stable; this condition is called a temperature inversion and occurs when warm air over cold ocean or land cools at the zone of contact. Warm upper air over a cold ocean has no chance to descend and pick up its moisture. Warm air over a cold nocturnal desert is stable but gives way to unstable air, and "dust devils," as the desert warms in the daytime.

Atmospheric Global Circulation

When the sun's heat warms equatorial air, the air expands and rises. (On rising it cools, and since cold air holds less moisture, this causes the heavy tropical rains; here we anticipate our section on rainfall.)

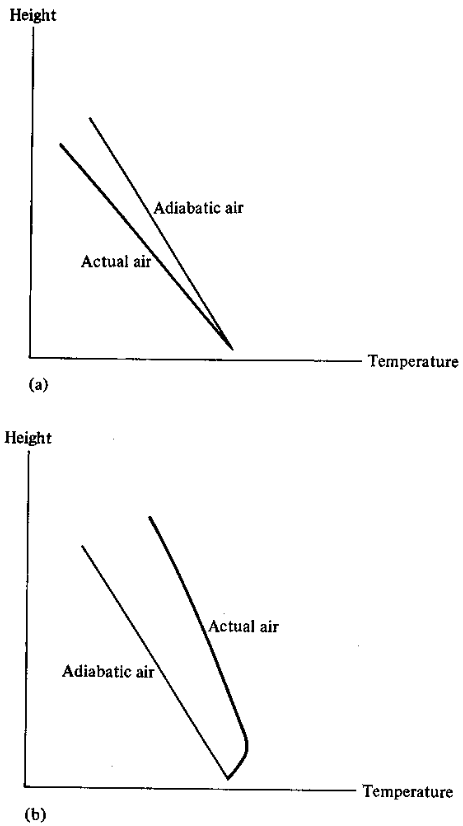

Fig. 1-4

(a) When the actual air cools more rapidly than adiabatic air, with height, it is unstable. (b) When the actual air cools less rapidly than adiabatic it is stable. The figure shows a very stable temperature inversion, with warm air over colder.

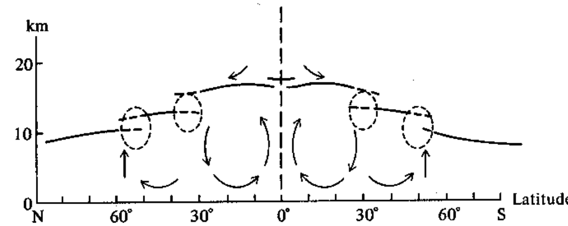

Fig. 1-5

Direction of circulation of the earth's atmosphere, shown by the arrows. The dashed circles are "jet streams." For a discussion see the text. (After Flohn, 1969.)

But the rising air must be replaced by other air, so we can infer surface winds on the earth rushing toward the equatorial regions to replace the rising air. (These are the trade winds, and we will see in the next section why they deflect to come from northeast and southeast.) The rising air does not go up forever, of course. Rather, it spreads out and, for no very clear reason, falls again at about 30°N and S latitude (see Fig. 1-5). There we have cool, dry air warming as it falls toward the earth; it can pick up more moisture and certainly has none to lose; hence we get our first hint of why deserts are usually at this latitude. The rest of the circulation pattern is hard to explain, but it at least has all the air going somewhere and coming from somewhere.

Coriolis Force

Hard as it is to account for the air movements of Fig. 1-5, they are the key to the explanation of the rest of the climate patterns. But we need one more tool, Coriolis force, which will show us why moving objects in the Northern Hemisphere deflect right and moving objects in the Southern Hemisphere deflect left.

The surface of the earth rotates from west to east, making the sun appear to rise in the east and set in the west. At the equator, the earth's surface is far from its axis of rotation, so it moves rapidly. Since the earth is about 24,000 miles around at the equator, the surface moves at a rate of 24,000 miles/day and so does any object on the surface. Farther north, at, say, 45°N latitude, the parallel of 45° latitude is only cos 45° = 0.707 times as long, which is just under 17,000 miles. Hence an object on the earth's surface at this latitude is moving at a velocity of 17,000 miles/day. In other words, at higher latitudes the surface moves more slowly.

Now picture an object moving north from the equator. While at the equator it had no east → west motion relative to the earth and so was, like the earth's surface, moving east at 24,000 miles/day. By the law of conservation of momentum it will tend to keep this much west → east momentum even when it reaches a more northern latitude, where the earth's surface itself is going more slowly. Hence, on moving north, our object will deflect right. Reversing the argument for another object, one moving from north latitudes toward the equator, we see it will tend to deflect west, but this can still be viewed as deflecting right. Therefore, we say that any object moving on the earth's surface in the Northern Hemisphere tends to deflect right; and similarly, moving objects in the Southern Hemisphere tend to deflect left.

Now we can explain winds and ocean currents. The trade winds rushing from the north toward the equator to replace the hot rising air deflect right and are thus coming from the northeast—they are the northeast trades. They pile up water as they blow along, so the Atlantic Ocean is deeper where the trade winds have pushed it into the Caribbean against Central America. In fact, the water on the Atlantic side of the isthmus of Panama averages a few feet higher than that on the Pacific side. This piled-up water escapes northward as the Gulf Stream. With its own Coriolis force it continually deflects right, around past England, down the west coast of Europe, and back toward the Caribbean. Wherever the trade winds can push the oceans against suitable barriers, they pile up the ocean water and cause ocean currents that move toward the poles on east sides of continents and then across the oceans and back toward the equator on the west sides of continents, the general deflection of the circulation always being that of Coriolis force (Fig. 1-6).

We shall return to these currents presently as they are of immense importance, but first we must discuss the cause of the prevailing westerly winds at temperate latitudes in both Northern and Southern hemispheres. We saw in Fig. 1-5 that there is in each hemisphere a poleward motion of the surface air from latitudes 30°N and S. Deflecting right

in the Northern Hemisphere or left in the Southern, this motion will take a westerly component. Furthermore, the upper atmosphere is higher in midlatitudes than at high latitudes (refer to Fig. 1-5 again). In other words, above a given altitude there is more air at midlatitude than at high latitudes, and hence the pressure is greater at midlatitude. Air thus tends to move poleward in this zone and, deflecting right, forms a belt of westerly winds called the westerly jet. This belt of winds attains such a velocity that its Coriolis force southward balances the force northward that initiated the jet. Commercial planes often use these jet streams to get an extra 100 or 150 mph ground speed in their eastward flight. Hence both the surface and the upper air seem to have a strong westerly component north of 30°N latitude and south of 30°S latitude. (In the Southern Hemisphere at about 40°–50°S latitude there isn't much land to get in the way of these winds, and they are known as the "roaring forties." In 1854, the clipper ship *Champion of the Seas*, running east toward Australia in the roaring forties, went 465 nautical miles in 24 hours; but to beat westward against these winds especially through the Straits of Magellan proved too difficult for many a sailing ship.)

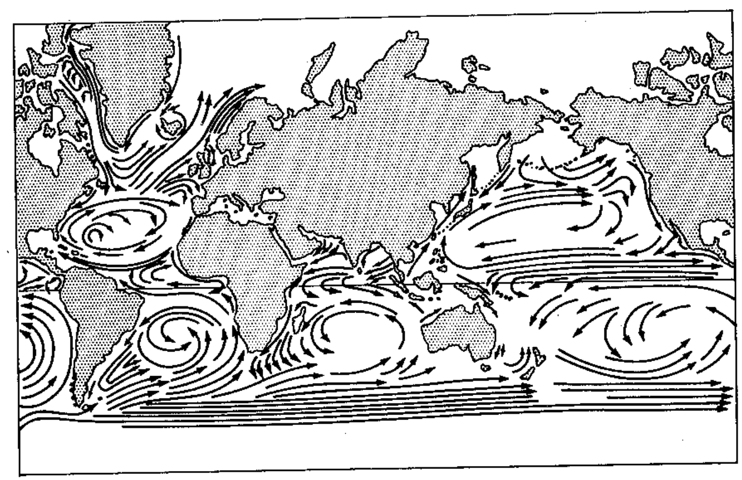

Fig. 1-6

Pattern of world's ocean currents. (From MacArthur and Connell, 1966.)

World Rainfall Patterns

Now we have the main elements in our explanation of the winds and the ocean currents. In combination they will account for the world's great rainfall patterns. In the trade wind zones the warm air picks up moisture from the oceans. When these moist trade winds hit a mountainous island or bit of mainland, their air goes up, cools, and loses large amounts of water. These same winds descending on the lee side of the mountains warm again and are thirsty for moisture; hence there is often a dramatic "rain shadow" on the southwest of tropical islands (in the Northern Hemisphere). Puerto Rico, for instance, gets heavy rain on its mountains but is a desert with succulent tree-like cactus species, reminiscent of Arizona, on its southwestern edge. Central America similarly tends to have a heavy rainfall where the trade winds hit the coast, but there is a rapid reduction in rainfall toward the Pacific slope, which is dry and even desert-like.

In the temperate zones our story involves the prevailing westerlies and the ocean current moving equatorward down the west sides of the continents. This current tends to be warmer than the land at high latitudes. Here the westerlies pick up moisture and, on cooling over the land, drop heavy rains. That is why the coast of British Columbia and that of southern Chile are drenched with almost continual rains (especially in the winter; then the offshore currents are much warmer than the land). Proceeding farther toward the equator along the same currents, two things change. First, the land gets warmer; second, the currents actually get colder at the ocean surface. The reason for the first is obvious, but the second requires explanation. Anyone who has swum off the coast of central California knows the water is cold, but why? There is, in this region, a wind paralleling the ocean current down the coast, which here runs from northwest to southeast. This wind moves faster than the current and thus exerts a dragging force that makes the surface of the current try to accelerate. Of course, this surface deflects right, pulling up bottom water to replace it. Thus there is upwelling, bringing cold (nutrient-rich) water from the bottom to the ocean surface. (The rightward deflection of the surface of the current causes an offshore motion of such velocity that *its* Coriolis force backward along the current just cancels the wind's force; hence a stronger wind causes stronger upwelling.)

Now our entire story changes. In discussing currents warmer than the land, we had westerlies picking up moisture from a warm ocean and dropping it on the cool land. But what happens if the ocean is cooler and the land warmer? When the land is warmer than the ocean, the westerlies do not drop rain but instead are thirsty for additional moisture. Only the cool mountains in such regions get rain. Northern California and Oregon are warmer than the ocean in the summer and get little rain; in the winter they are colder and have almost continuous rain. Southern California is almost always warmer than the ocean and, except in the mountains, gets virtually no rain. (San Diego gets only 10.11 in./year.) Baja California is even drier because it is warmer, and it is called desert although it is sparsely clothed with exotic succulents and cacti. (See the outstanding Sierra Club book *The Geography of Hope* for beautiful photographs and well-written commentary on Baja California.) Exactly the same pattern is repeated going north along the coast of Chile. Within that very long country one can proceed from cool rain forests so dense that Darwin had to walk over the top (without falling through), north through Mediterranean climate with citrus and grapes, like California, and farther north to the Atacama desert, the driest spot on earth. Some places there have never recorded rain. Of course, it is no accident that these deserts are on west sides of continents at about 30° latitude, and we can now summarize three main reasons for their location: (1) Cool dry air is descending and warming at 30° latitude (Fig. 1-5). This air will tend to pick up moisture if any is available; it won't lose any. (2) Prevailing westerlies blow in across a cold ocean. The temperature inversion, with cold air just above the cold ocean, is stable and the winds pick up little water. They then pass over warm land and would tend to pick up rather than lose moisture. (3) What little water the westerlies do have is usually lost as the winds pass over cool mountain ranges. The coastal ranges of California and Chile leave drier valleys farther inland, and the deserts of Arizona and California are in the rain shadow of the Sierras.

The rainfall as we proceed toward the eastern side of a continent is not just a consequence of the moisture the prevailing westerlies have picked up. We must also consider air masses. Looking at Fig. 1-5 again, we see that the air poleward of about 50° latitude is distinct from that equatorward. Between 30° latitude and 50° latitude the air moves poleward (and deflects toward the east) and is thus warm air. It is called tropical air even though it isn't really of tropical origin. In eastern United States and Canada, this warm air is often laden with moisture from the Gulf of Mexico or the Atlantic. This air mass meets the polar air mass that lies north of the westerly jet stream. If this were a complete picture, we would expect heavy rains only at latitude 50°. In fact, the jet stream meanders and breaks into eddies and vortices, leaving a belt of storms that spread over a much wider range of latitudes. The eastern parts of North America get most of their rains from cyclonic storms of this kind, distributed fairly evenly throughout the year.

Thunderstorms increase in importance toward the southeast, where parts of Florida get about 80 thunderstorms a year compared to 20–30 received by the northeast. When the ground heats during a hot day, it warms the lower air and causes an atmosphere that cools faster than adiabatically with elevation. Such an atmosphere, as we have seen, is unstable, allowing shafts of adiabatic air to penetrate and prosper. These set up strong updrafts, which are associated with the huge cumulonimbus

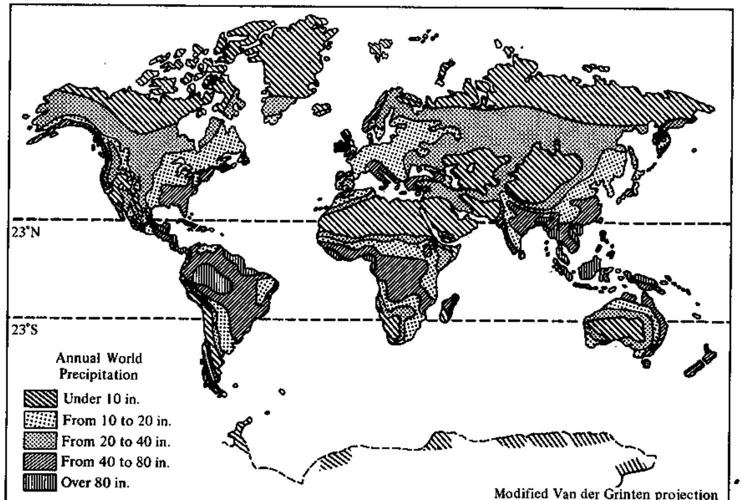

Fig. 1-7

Pattern of world precipitation. (From MacArthur and Connell, 1966, after Koeppe.)

thunderheads. At some point they are cooled enough to initiate a thunderstorm. Such storms may drop a total of 30–40 inches of rain per year on Florida and lesser amounts elsewhere. Even the Arizona deserts count on their summer rains from Gulf Coast maritime air persuaded to lose its moisture by thunderstorms in an unstable atmosphere. For the world pattern of precipitation, see Fig. 1-7.

Proximity to oceans or other large bodies of water that are heat reservoirs has a great moderating effect on temperature; the interiors of continents, far from oceans, are said to have a "continental" climate, having cold winters and hot summers. This is clear on comparing Wisconsin and Michigan. Wisconsin has very cold winters, but the westerlies blow on across Lake Michigan, which is a huge heat reservoir, and Michigan winters are much warmer.

There is at least one more important cause of rainfall, and it has produced the heaviest rains ever recorded. In summer, as continents warm faster than the oceans and the air above them rises, we get strong winds literally sucked in off the oceans. These are the monsoons. When they hit mountains, they lose prodigious amounts of water. Cherrapungi, India, received 366 inches (over 30 feet) of rain in one month, July 1861, as a result of exceptionally heavy monsoons.

One other point about rainfall should be mentioned. We who live in the temperate zone are familiar with "storms." We hear of one approaching from the west and whirling across the continent, and we prepare for several days of bad weather. Sometimes there may be as many as 10 days with rain every hour. Sometimes also these storms are accompanied by severe cold, freezing rain, or very strong winds. Table 1-1 shows a comparison of rainfall duration in temperate and tropics, indicating clearly that New Jersey storms are of longer duration than those on Barro Colorado Island, Panama Canal Zone. In the temperate regions and the very edge of the tropics there are so-called tropical storms that we call hurricanes and others call typhoons, and that often do severe damage on the east coast of the United States. Such storms as these—even the hurricanes—are largely unknown in the real tropics and never occur within 5° of the equator (Byers, 1954). There may be seasons of the year with and without trade winds; there may be wet seasons and dry seasons, and there may be daily rains. But except in regions of exception-

Table 1-1
Comparison of Rainfall Duration in Temperate and Tropics, 1967

	Number of rains	
Duration of rain (hr)	Trenton, N.J.	Barro Colorado Island, Panama Canal Zone
$\geqslant 1$	186	415
$\geqslant 5$	73	26
$\geqslant 10$	38	2
$\geqslant 15$	21	1
$\geqslant 20$	11	1
$\geqslant 25$	5	1
$\geqslant 30$	2	0
Mean duration (hr)	6.242	1.945

ally heavy rainfall, these are usually of short duration, and even though much rain falls the sun is soon out again, the insects flying, and the birds feeding once more.

Appendix Derivation of Adiabatic Lapse Rate

Here we derive the dry adiabatic lapse rate from the gas law $pV = RT$ (p = pressure, V = volume, R is a constant, and T = absolute temperature) and from the first law of thermodynamics that says that when no heat is added to a volume of gas (i.e., adiabatic) $c\,dT = -p\,dV$ where c is the specific heat at constant volume and equals $\frac{5}{2}R$ and dT and dV are differentials of temperature and volume. We must also calculate how pressure changes with altitude by considering a column of gas of unit cross section. At height $h + dh$ the pressure will be lower than at height h by the weight of the cylinder of gas of unit cross section and height dh. This weight is $w\,dh$ where w is the weight of unit volume of gas at that altitude. $w = g\dfrac{M}{V}$ where g is the acceleration of gravity, 980.665 cm/sec^2, M is the molecular weight of the gas, and V is the volume occupied by 1 mole. In other words, $dp = -g\dfrac{M}{V}dh$ or $V\,dp = -gM\,dh$. Taking differentials of the gas law, $p\,dV + V\,dp = R\,dT$, whence the first law can be written $(c + R)\,dT = V\,dp$, and equating values of $V\,dp$, we finally get $(c + R)\,dT = -gM\,dh$, so the change of temperature T with respect to elevation h is given by

$$\frac{dT}{dh} = -\frac{gM}{c+R} = -\frac{980.665 \times 28.88}{\frac{5}{2}(8.214 \times 10^7) + 8.214 \times 10^7}$$

$$= -\frac{28321.605}{28.749 \times 10^7} = -985 \times 10^{-7}\,\frac{\text{deg}}{\text{cm}} = -9.85\,\frac{\text{deg}}{\text{km}}$$