D

DEGREE DAYS

The degree-day is an index number originally developed by heating, ventilation, and air conditioning engineers (Houghton, 1985). The heating degree-day was developed to assess energy needs necessary to heat business buildings and private homes. The heating degree-day index assumes that people will begin to use their furnaces when the mean daily temperature drops below 65°F. It is computed by subtracting the mean temperature for a day from 65°F to determine the total number of heating degree-days for a given day. When the mean daily temperature is above 65°F there are no heating degree-days. The greater the range in a mean daily temperature from 65, the greater the number of heating degree-days; hence, more fuel must be expended (Ahrens, 2001).

The cooling degree-day is used to assess energy needs required to cool buildings and homes. When the mean daily temperature exceeds 65°F people will begin to employ measures to cool their environment by switching on their air-conditioners and cooling pumps. The cooling degree-day index is computed by subtracting 65°F from the mean daily temperature. If the two temperatures are the same, there are no cooling degree-days. The greater the range in a mean daily temperature from 65, the greater the number of cooling degree-days; hence, more power must be expended to maintain a comfortable environment. Cooling degree-days provide a guide for builders when planning the size and type of cooling units to install in structures. Power companies may use these data to predict energy demands throughout a summer season. When combined, the heating and cooling degree-day indices provide a practical way of assessing energy requirements for a region throughout the year.

The freezing or thawing degree-day is a measure of the combined duration and magnitude of below or above freezing temperatures during a freezing season. It is designated as an air freezing/thawing index when taken for air temperatures 4.5 ft above the ground, and surface freezing/thawing index for temperatures immediately below the surface. The freezing/thawing degree-day (FDD) is used to assess conditions related to problems with highway construction, soil disturbance involving mass movements, and foundation assessment due to groundwater through flow and sapping processes resulting from freeze/thaw conditions.

Table D1 Base temperatures for selected crops and insects. By reviewing the climate data for a region and comparing mean daily temperatures, growing degree-days can be computed for a crop

Crops and insects	Base temperatures
Wheat, barley, rye, oats, flaxseed, lettuce, asparagus	40° F
Sunflower, potato	45° F
Sweet corn, corn, sorghum, rice, soybeans, tomato	50° F
Corn rootworm	44° F
Alfalfa weevil	48° F
Black cutworm, European corn borer	50° F
Green cloverworm	52° F

The growing degree-day is used by farmers as a guide for planting and estimating when a crop will be ready for harvest; and closely associated with crop production, the peak time of a season in which crop-destroying insects occur. The growing rate or biological development in plants and insects is based in part upon the amount of heat absorbed during a growing season of a plant or the life cycle of an insect. Each species, whether crop, weed, insect, or disease organism, is adapted to grow over a certain minimum (base) temperature, and decline in growth at a maximum temperature. The quantity of heat absorbed as a requirement of sustained growth and development is often referred to as a heat unit or degree-day. By subtracting the base temperature (Table D1) for a given crop from the daily mean temperature, the number of growing degree-days may be computed. When growing degree-days are totaled, farmers can establish an estimate of the minimum number of days of growth required for a crop until it is ready for harvest. While this index provides a quick guide for crop development, soil moisture properties, precipitation amounts, and other climatic variables are not considered in this general format.

Discussion

The *Handbook of Applied Meteorology* (Houghton, 1985) discusses the degree-day on the basis of heating or cooling requirements, growing degree-days, or freezing/thawing degree-days. Degree-days are generally quantified from a threshold or base temperature determined for each condition, i.e. cooling, heating, growing, or freezing/thawing degree-days. Threshold temperatures include:

1. 65°F (18°C) for cooling energy requirements generating cooling degree-days (CDD), and expressed as, $CDD = \Sigma(\check{T}_i - A)$ where, $\check{T}_i$ is the mean daily temperature for a day i, A is a threshold temperature, and Σ is the summation over a period of days, such as a week, month, or season. If $\check{T}_i$ is $<$ 65°F, CDD is 0.
2. 65°F (18°C) for heating energy requirements generating heating degree-days (HDD) with the equation written as, $HDD = \Sigma(65 - \check{T}_i)$. If $\check{T}_i$ is $>$ 65°F, HDD is 0.
3. Variable base temperatures (B) for growing degree-days (GDD) dependent upon crop type where, $GDD = \Sigma(\check{T}_i - B)$, and B is a base temperature for a given crop type. If $\check{T}_i < B$, GDD is 0. Growing degree-days are similar to cooling degree-days, only the base temperature can vary with different plant types in computing growing degree-days, while the threshold temperature for cooling degree-days generally remains constant at 65°F.
4. 32°F (0°C) for freezing degree-days (FDD) where, $FDD = \Sigma(32 - \check{T}_i)$. If $\check{T}_i$ is $>$ 32°F, HDD is 0. By extension, thawing degree-days (TDD) are computed as, $TDD = \Sigma(\check{T}_i - 32)$. If $\check{T}_i$ is $<$ 32°F, TDD is 0.

Degree-day values have been used to show that climate change models may not adequately explain the energy expenditures that would be expected with reported increases in mean temperatures, increases in extreme high temperatures, and increases in the frequency, duration, and magnitude of summer heat waves. Hansen et al. (1998) developed a common-sense climate index using degree-days and reported that parts of North America are showing changes consistent with climate model predictions given increasing levels of greenhouse gases. A graph for New York City's LaGuardia airport shows a decrease in heating and cooling degree-days for the past few decades. Balling (1999) analyzed temperature data derived from NOAA's Daily Historical Climatology Network for the conterminous United States from 1950 to 1995. He computed and plotted the heating, cooling, and total degree-days for this time period. His graph paradoxically shows no statistically significant trends throughout this time. He reports a 0.2% decrease in heating degree-days, 5.7% decrease in cooling degree-days, and a 1.0% decrease in total degree-days. When considering climate change and energy needs, this slight decrease in cooling degree-days would indicate a reduction in the energy needs to cool buildings, and is contrary to what would be expected with warming trends. The period of time reviewed in this study was one of substantial buildup of greenhouse gases throughout the Earth's atmosphere. Numerous climate models for global warming suggest that a decrease in heating degree-days and increase in cooling degree-days would follow rises in these greenhouse gases, yet the analysis of degree-day patterns from the historical climate record for this 35-year period does not provide empirical evidence to support these climate model simulations.

A climatic classification using degree-days has also been reported. The somewhat generalized nature of this classification does not appear to provide a significant contribution toward the enhancement of the more widely accepted climate classification systems since it only addresses degree-days with respect to ordinal-scaled (e.g. very severe, severe, moderate, mild, warm, or hot) seasonal characteristics. Figure D1 (Houghton, 1985) illustrates this classification for the eastern United States.

Phenology models

The degree-day concept is fundamentally simple in design, but it has limits when used to determine growing degree-days for agricultural use. Phenology models predict time of growth events for organisms (insects and plants). Plants and insects require a minimal amount of heat to develop throughout their life cycles. An accumulation of heat units is called physiological time, and it is measured in degree-days (°D). Degree-day methods provide scientists with quantitative methods used to assess the physiological time of organisms. Estimating heat units or accumulated degree-days provides a more biologically accurate snapshot of an organism's stages of development than using calendar days based upon variations in yearly climate records.

Organisms (plant and insect) develop faster when temperatures are higher, although this does not imply there is a yield or quality benefit in warm seasons. While organisms will grow faster in warmer temperatures, and they are exposed to greater heat for fewer days, the net accumulation of heat units (degree-days) required for development is about the same as for organisms developing under cooler conditions for more days. Since temperatures fluctuate from cool to hot during a growing season, it is the total heat accumulation derived between the lower and upper threshold temperatures for each plant species that determines the time to complete development. Plant development ceases when a temperature falls below a lower threshold, and also begins to decline and ultimately stop development when the temperature exceeds an upper threshold. In some cases the maximum temperature can exceed the base temperature for a plant, thus 0 growing degree-days are accumulated, e.g. if a maximum temperature is 60°F, a minimum temperature is 35°F, then the average daily temperature is $(60 - 35)/2 = 47.5$°F. If the base temperature for this plant = 50, then $47.5 - 50 = -2.5 = 0$ degree-days. This example results in 0 growing degree-days (an underestimation), although the average temperature used in the calculations is above the lower threshold for the plant.

When temperatures become excessively hot, the degree-day system will give heavy weighting to these temperature extremes that can actually be detrimental to the plant. A modified growing degree-day provides an adjustment for high temperature extremes. If a temperature exceeds a threshold high (Figure D2) for a given plant, it is adjusted back to the threshold. Alternatively, if the lowest temperature is below the threshold low (Figure D2) for a plant, it is adjusted up to the threshold. Once the temperatures have been adjusted, the average daily temperature is computed and used to compute growing degree-days. Threshold temperatures are used for certain crops (e.g. corn) and based on the assumption that development is limited once a threshold low or high is exceeded.

While degree-days are generally based upon a mean daily temperature (maximum daily temperature − minimum daily temperature/2), the influence of diurnal patterns is lost when only considering these temperature extremes. Computing growing degree-hours (GDH) may provide a more representative way of assessing variability in the daily temperatures. Mimoun and DeJong (1999) have documented that accumulated

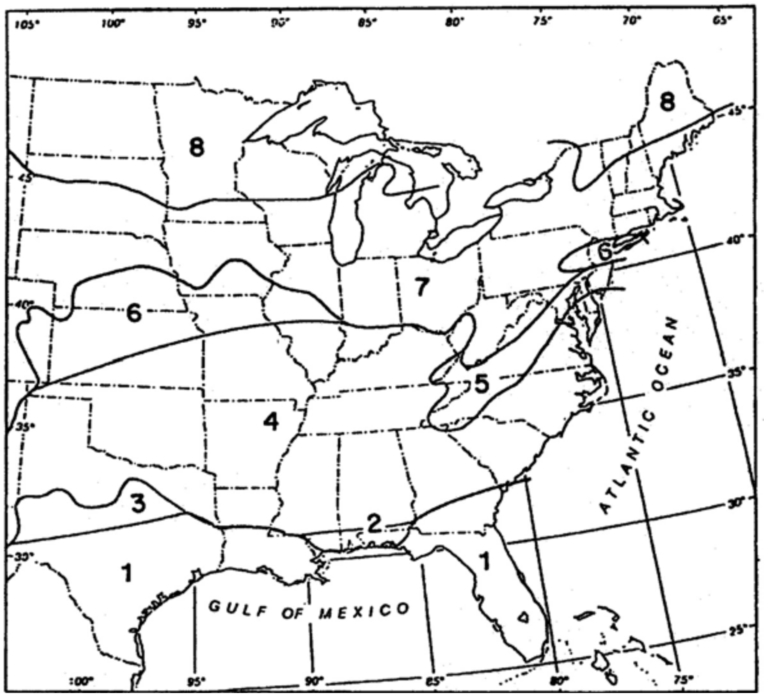

Figure D1 A climatic classification of the United States using heating (HDD) and cooling (CDD) degree days. Key:

	Winter	HDD	Summer	CDD
1	Mild	<2000	Hot	>2000
2	Mild		Warm	1000–2500
3	Moderate	2000–4000	Hot	
4	Moderate		Warm	
5	Moderate		Mild	<1000
6	Severe	4000–8000	Warm	
7	Severe		Mild	
8	Very severe	>8000	Mild	

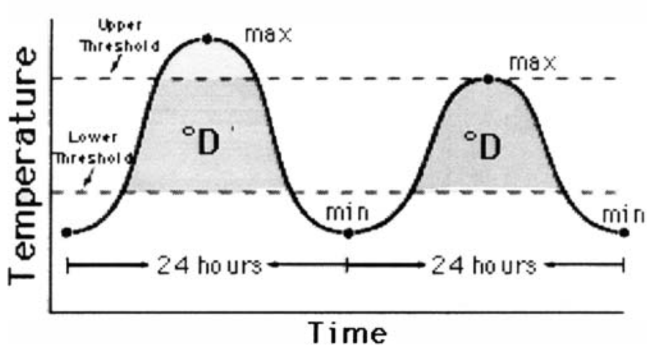

Figure D2 Thresholds (dashed lines) and area representing degree-days (shaded) for 24-hour time periods (from the University of California, Pet Management Program, 1990).

temperatures (in growing degree-hours) for 30 days after bloom are highly correlated with yearly differences in harvest date for peaches, plums, and nectarine cultivar. A general use would be to compare records of bloom dates (when 50% of the flowers on a tree or orchard are fully open) and harvest dates for previous years, look for a year with a comparable GDH accumulation (at 30 days after bloom), and expect the number of days from bloom to harvest will be similar to that year.

Seasonal variances and climatic region can also impact how accurately a degree-day method represents actual degree-days. Several refinements in computing degree-days have been reported (Allen, 1976; Wilson and Barnett, 1983; Zalom et al., 1983). These methods include (from the simplest to the most mathematically complex): single triangle, double triangle, single sine, double sine, and Huber's method (a modification of the single sine method). Each has been applied to determine heat units required for insect development, and by extension to agricultural development since insects can have a pronounced and detrimental affect on annual crop yield. These methods are based on the area under a diurnal temperature curve and between critical threshold temperatures.

The degree-day computational techniques including the cutoff methods that establish parameters for the upper and lower threshold temperatures are discussed in University of California, 1990, Zalom et al. (1983), and at the web site for University of California, Davis, (http://www.ipm.ucdavis.edu/WEATHER/ddconcepts.html).

Summary

The degree-day was initially designed by heating and cooling engineers to assess the cooling and heating needs of business buildings and homes. A number of procedures for computing degree-days have been presented in this discussion. The more robust mathematical models (triangle and sine methods) tend to provide more credible results than those models that only use the mean daily temperature. Growing degree-days have been used to study pest management and further applied in agricultural studies. An ordinal climatic classification has also been proposed, although it does not provide any significant contribution to the more widely accepted climate classification systems.

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Cross-references

Agroclimatology
Climate Change and Human Health
Spring Green Wave
Vegetation and Climate

DESERTIFICATION

The prolonged multiyear drought in the early 1970s in the Sahelian zone, stretching from West Africa to the Horn of Africa, precipitated a sharp increase in death and morbidity of humans and livestock, as well as widespread environmental deterioration. Stark satellite images capturing the degradation of the land surface throughout the region were backed up by ground-truth photographs of the landscape and human suffering.

Although many articles, papers, and reports from various countries begin with comments on the role of the Sahelian drought in the growing interest in desertification (e.g. Glantz, 1977; UN Secretariat of the Conference on Desertification, 1977; Quintanilla, 1981; Zonn, 1981), that drought was neither the first manifestation of the desertification phenomenon nor the only reason for scientific interest in it. In fact, Aubreville (1949), a French scientist, was the first to use the term "desertification" in his report, and others (e.g. Le Houérou, 1962) have discussed the phenomenon since the late 1950s. Desertification received immediate and widespread public attention ever since the early 1970s, as witnessed by the creation of the United Nations Conference on Desertification (UNCOD) in Nairobi in 1977. It was clear that the conference was convened mainly as a result of the devastating impacts of drought in the West African Sahel earlier in the decade.

This conference brought the concept of desertification and its demographic aspects into the spotlight (UN Secretariat of the Conference on Desertification, 1977). The conference report described desertification in the following way:

> The diminution or destruction of the biological potential of the land . . . can lead ultimately to desert-like conditions. It is an aspect of the widespread deterioration of ecosystems, and has diminished or destroyed the biological potential, i.e., plant and animal production, for multiple use purposes at a time when increased productivity is needed to support growing populations in quest of development. Important factors in contemporary society – the struggle for development and the effort to increase food production, and to adapt and apply modern technologies, set against a background of population growth and demographic change – interlock in a network of cause and effect. Progress in development, planned population growth and improvements in all types of biological production and relevant technologies must therefore be integrated. The deterioration of productive ecosystems is an obvious and serious threat to human progress. In general, the quest for ever greater productivity has intensified exploitation and has carried disturbance by man into less productive and more fragile lands.
>
> Overexploitation gives rise to degradation of vegetation, soil and water, the three elements which serve as the natural foundation for human existence. In exceptionally fragile ecosystems, such as those on the desert margins, the loss of biological productivity through the degradation of plant, animal, soil and water resources can easily become irreversible, and permanently reduce their capacity to support human life. Desertification is a self-accelerating process, feeding on itself, and as it advances, rehabilitation costs rise exponentially. Action to combat desertification is required

urgently before the costs of rehabilitation rise beyond practical possibility or before the opportunity to act is lost forever (Reining, 1978, p. 3).

The 1977 Nairobi conference also served to bring together representatives of countries whose arid and semiarid landscapes had been directly or indirectly affected by desertification processes. More than a score of governments produced and shared their national case studies about desertification processes within their borders. The actual usefulness of this conference varied from country to country. It became quite clear that desertification was a local to national-level problem with transboundary impacts. It is listed among major global problems because of its occurrence and interest worldwide.

For some countries, such as the People's Republic of China, the conference drew the attention of national policy makers toward arid lands research and helped to elevate such research to a sustained national priority. It remains a high priority more than 25 years after UNCOD. The former Soviet Union's State Committee for Science and Technology (GKNT) established, with the United Nations Environment Program (UNEP) support, international training courses on various aspects of desertification (e.g. overgrazing, salinization, woodcutting) and on ways to identify and combat them (Plit et al., 1995; Zonn, 1981). Today, almost all of the arid parts of the former Soviet Union are within independent countries of Central Asia. Nevertheless, the Russian Federation contains in its Kalmykia Republic the only desert in Europe (Saiko and Zonn, 1997).

In the United States the attention of national policy makers was directed at the time toward environmental degradation in arid areas, and a plan of action was drawn up to assess desertification in a national context (Sabadell et al., 1982). However, the US government refused to admit that desertification processes were taking place on its soil. It believed that desertification was a Third World problem, even though the US rangelands were being overgrazed, dust storms were occurring, and salinization and waterlogging of the soils could be witnessed.

Desertification is a complex multifaceted phenomenon, requiring the expertise of researchers in disciplines such as climatology, soil science, meteorology, hydrology, range science, agronomy, ecology, veterinary medicine, as well as geography, political science, economics, and anthropology. It has been defined in different ways by researchers in these and other disciplines, as well as from national and bureaucratic (institutional) perspectives, with each perspective emphasizing different aspects of desertification of concern to it. Scores of definitions exist for the concept, so it is important to know what one is referring to when discussing desertification processes.

At one time desertification as a process was of particular interest to climatologists in their attempts to understand climate variation and change on both short and long time scales (e.g. Charney, 1975; Hare, 1976). With increasing pressure on government decision makers to allow populations to move into climatically marginal areas, the implications of natural variations in climate have become even more important in decisions relating to the use by society of its land in desertification-prone regions. There will always be climatic deserts on the Earth, although their locations can shift. Human-induced expansion of these desertlike conditions can take place in areas where they had not previously existed.

Desertification literature shows a great diversity (and confusion) among definitions (e.g. Carder, 1981). The wide range of meanings attributed to the concept leads to misunderstandings *among* physical and social science researchers and policy makers, as well as *between* researchers and policy makers (see International Geophysical Union Working Group on Desertification, 1975, *passim*). An analysis of the definitions of desertification helps to improve understanding of the phenomenon, of how it is viewed from different disciplines, countries, and bureaucratic units, and whether progress in combating it has in fact been as slow as many observers suggest (e.g. Glantz and Orlovsky, 1986; UN General Assembly, 1981). Scientific interest in desertification remains high, because, as Reynolds and Smith (2002) noted,

> There is disagreement concerning the causes and processes of land degradation and its importance; the extent to which land changes are natural (climate-driven) versus anthropogenic; the role of "grass roots" abatement efforts versus scientific and technological ones; how to determine the amount of land affected or at risk; and whether or not desertification is reversible.

Various reviews of the progress to combat desertification processes worldwide exposed limited successes in isolated situations. Some of the scientists who in the 1970s and early 1980s had written about those adverse conditions were, by the end of the 1980s, suggesting that natural causes of desertification in the West African Sahel were dominant. Thus, scientific papers were beginning to challenge the hypotheses about the irreversibility of desertification and about the dominance of influence on the fragile environment of human activities in the region. In other words, desertification is, under certain conditions, reversible in spite of human pressures on fragile arid, semiarid, and dry subhumid ecosystems.

According to the UNCCD (UN Convention to Combat Desertification) website, at the Earth Summit (the UN Conference of Environment and Development, or UNCED) in Rio de Janeiro in 1992, delegates supported a

> new, integrated approach to the problem, emphasizing action to promote sustainable development at the community level. It also called on the UN General Assembly to establish an Intergovernmental Negotiating Committee to prepare, by June 1994, a convention to combat desertification, particularly in Africa. In December 1992, the General Assembly agreed and adopted Resolution 47/188 (www.unccd.int).

The UNCCD entered into force in December 1996, after the fiftieth ratification by a government was received. The Conference of Parties, the Convention's supreme governing body, held its first session in October 1997 in Rome, Italy. The UNCCD also noted that

> The Convention aims to promote effective action through innovative local programs and supportive international partnerships. The treaty acknowledges that the struggle to protect drylands will be a long one – there will be no quick fix. This is because the causes of desertification are many and complex, ranging from international trade patterns to unsustainable land management practices. Difficult changes will have to be made, both at the international and the local levels (www.unccd.int).

In the following sections these definitions are used as the basis for discussion, as they are often what is seen and used by decision makers. In the last section it is argued that the concept of desertification also applies to higher rainfall regions than those cited by contemporary arid lands researchers.

Desertification: a process or an event?

Some people consider desertification to be a *process* of change (degradation), whereas others view it as the *end result* of a process of change (a desertlike landscape). This distinction underlies one of the main disagreements on what constitutes desertification. Desertification-as-process has generally been viewed as a series of incremental (sometimes stepwise) cumulative adverse changes in biological productivity in arid, semiarid, and dry subhumid ecosystems. It can encompass decline in yield of the same crop or, more drastically, the replacement of one (maybe equally productive or equally useful) vegetative species by another, or as a decrease in the density of the existing vegetative cover. Desertification-as-event is the creation of desertlike conditions, where perhaps none had existed in the recent past, as the end result of a long-term process of cumulative adverse changes. Many find it difficult to accept incremental changes, whether natural or human-induced, as a manifestation of desertification processes.

In fact, both perspectives represent different aspects of a broader overarching concept of desertification. Thus, seemingly different statements such as "the creation of desertlike conditions in areas once green", "the encroachment of desertlike conditions", or "the intensification of a desertlike landscape", as well as less drastic projections such as "changes in soil structure or in climate" or "the land is becoming less fit for range and crops", can be encompassed by the concept of desertification.

Form of change

Within the dozens of existing definitions of desertification, many words are used to describe the phenomenon. Some of them complement each other, whereas others appear to be contradictory. A point on which they all agree, however, is that desertification is an adverse environmental process. The negative descriptors used in these definitions of desertification include: deterioration of ecosystems (e.g. Reining, 1978), degradation of various forms of vegetation (e.g. Le Houérou, 1975), destruction of biological potential (e.g. UN Conference on Desertification, 1978), decay of a productive ecosystem (e.g. Hare, 1977), reduction of productivity (e.g. Kassas, 1977), decrease of biological productivity (e.g. Kovda, 1980), alteration in the biomass (e.g. UN Secretariat of the Conference on Desertification, 1977), intensification of desert conditions (e.g. Meckelein, 1980; World Meteorological Organization, 1980), and impoverishment of ecosystems (e.g. Dregne, 1976). More recent definitions continue to fall into one or another of the above categories.

Each of these terms suggests a change in landscape from a favored or preferred state (with respect to quality, societal value, or ecological stability) to a less preferred one. Depending on the particular definition, each has been used to describe the condition of vegetation, soils, moisture availability, or atmospheric phenomena. Other descriptors used in these definitions connote an expansive movement or a transfer of characteristics of a desertlike landscape into an area where such characteristics had not previously existed: extension, encroachment, acceleration, spread, and transformation. If one combined each of these negative and transfer descriptors with all the other factors cited in the existing definitions, desertification would encompass most kinds of environmental changes related to biological productivity (see Rozanov, 1981). UNEP (1992) produced the *World Atlas of Desertification*, which identified the location as well as threats of desertification processes around the globe (Figure D3).

What is being changed?

Different definitions have focused on changes either in soil (e.g. salinization), vegetation (e.g. reduced density of biomass), water (e.g. waterlogging), air (e.g. increased aridity), or land surface (e.g. increased albedo). Most of them, regardless of primary emphasis, also describe changes in biological productivity, with comments related to the type, density, and even socially determined value of vegetation.

Type-of-vegetation comments center on changes from desired (or accepted) species to less desired (or less accepted) ones. Such comments include a reduction in the proportion of preferred species having an economic or societal value, the lowering of yields of an existing preferred species, or a major ecological change such as species replacement.

Change in the density of the vegetative cover is an important factor acknowledged in many definitions of desertification. As density decreases, for example, the risks of wind erosion, water erosion, and the adverse effect of increased solar radiation on bare soils are increased dramatically. Surface albedo (reflectivity), also enhanced by a reduction in the vegetative cover, is a major contributor to desertification processes.

With respect to the value of vegetation, researchers have also referred to "lower useful productivity" (Johnson, 1977, p. 317), "reduced productivity of desirable plants" (Dregne, 1976, p. 12), "sustained decline in the yield of useful crops" (UN Secretariat of the Conference on Desertification, 1977, p. 17), and "loss of primary species" (Rapp et al., 1976, p. 8). However, the concern with the value of vegetation in desertification processes is not shared by all researchers. Some researchers have dismissed the value concern, suggesting that any type of vegetation that holds the soil in place is of value in the combat against desertification, whether or not it has an economic benefit for a given society.

As a final comment on what desertification is, it is important to note that disciplinary and institutional biases might appear in any given definition of desertification. For example, a meteorological bias might require that a change take place in the meteorological parameters of a given region, so that they become similar to those for a desert region (e.g. high evaporation rates, aridity, increased rainfall intensity, etc.). As another example, Meckelein (1976), cited in Kharin and Petrov (1977), alluded to the disciplinary bases for desertification when he wrote that desertification could be characterized by the following components: *climate:* increasing aridity (diminishing water supply); *hydrological processes:* runoff becoming more irregular; *morphodynamic processes:* intensification of distinct geomorphological processes (accelerated soil erosion by wind and water); *soil dynamics:* desiccation of soils and accumulation of salt; *vegetation dynamics:* decline of vegetation. It is important to note that, while one aspect of desertification processes could be arrested, others may appear (Prince, 2002).

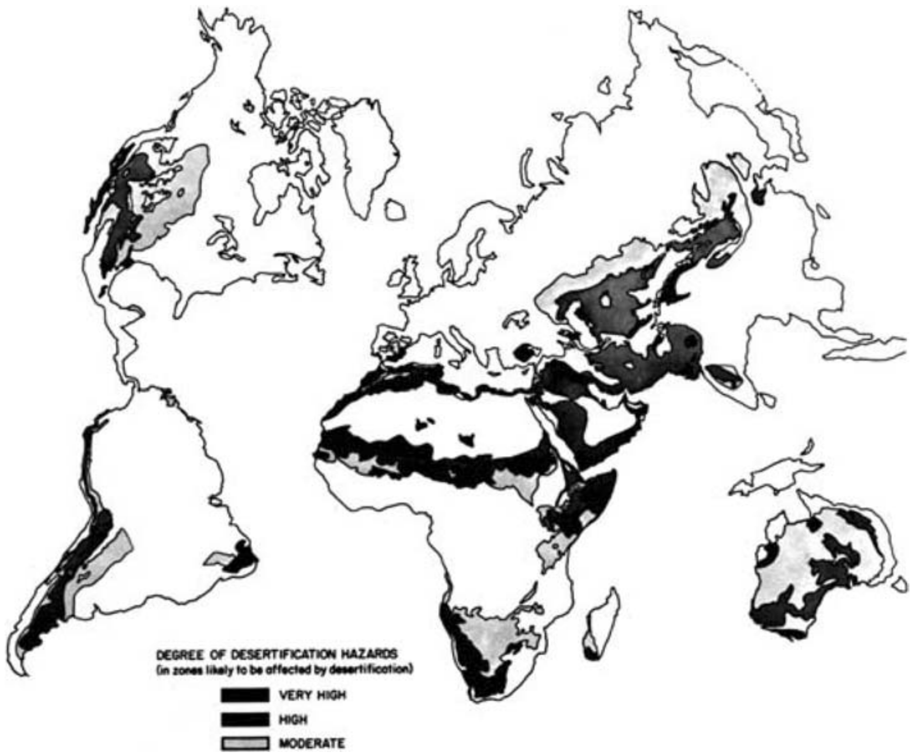

Figure D3 Degree of desertification hazards (in zones likely to be affected by desertification) (after *United Nations Map of World Desertification*, 1977; see also for comparison UNEP's *World Atlas of Desertification*, 1997).

Location of change

There is no agreement on where desertification can take place. Many researchers identify arid, semiarid, and sometimes dry subhumid regions as the areas in which desertification can occur or where the risks of desertification are highest. Others imply that the areas prone to desertification might not be restricted to arid, semiarid, or subhumid regions, by using such descriptive words as extension, encroachment, and spread of desert characteristics into nondesert regions. Still others (e.g. Mabbutt and Wilson, 1980) refer to the intensification of desertlike conditions, suggesting that desertification can occur in desertlike areas. Many oppose this view, however, contending that desertlike conditions cannot be created in a desert. They assert that desertification can only occur along the desert fringes. According to Le Houérou (1975), for example, desertification can occur only in the 50–300 mm isohyet zone.

Reversibility

Few definitions explicitly refer to whether or not desertification is permanent. Le Houérou (1975) briefly explained the conditions under which desertification (he called it "desertization") might be reversible. Others have implied reversibility with reference to the higher costs of rehabilitation of desertified areas (as opposed to prevention). For example, Adams suggested that the "reversibility of desertification was a function of technology and the cost of rejuvenating an area.... Irreversibility should refer to a situation in which the costs of reclamation were greater than the return from a known form of land use" (International Geophysical Union Working Group on Desertification, 1975, p. 138). Still others implied irreversibility by referring to the *end result* of desertification as the creation of desertlike conditions.

Two additional important considerations relating to the *in-situ* permanence of desertification are: (1) when desertification (as a process or event) might be reversed (i.e. the "time" factor); and (2) under what conditions (i.e. the "how" factor).

With respect to the time factor, some observers consider desertification to be irreversible during periods of up to several seasons but reversible on the order of decades and, if not decades, perhaps centuries. Peel "saw great danger in the concept of irreversibility because it has no time limitations whatever" (International Geophysical Union Working Group on Desertification, 1975, p. 138). One author has drawn a distinction between temporary and permanent desertification (Kove, 1982). Is it possible to distinguish between temporary desertification and, for example, seasonal environmental changes? Some have addressed this question by defining desertification as a sustained (as opposed to temporary) decline in biological productivity (e.g. Sabadell et al., 1982; UN Secretariat of the Conference on Desertification, 1977). Le Houérou, commenting on "what is temporary?", noted that, while temporary fluctuations may be interspersed with more favorable conditions, such a condition of successive crises does involve a progressively deteriorating situation, possibly past a threshold of irreversibility (International Geophysical Union Working Group on Desertification, 1975, p. 27).

How can desertification be reversed? Reversal might occur naturally, once the natural contributing causes have been removed. Otherwise, human intervention would be required (e.g. Kassas, 1977) if there is a desire on the part of decision makers to reverse it in less time than might be required to do so naturally. Chinese scientists have actively pursued programs for the past few decades designed to reverse desertification in China. In a 1990 speech the Executive Secretary of the UN Convention to Combat Desertification used China as an example of the threats imposed by desertification. His comments echoed those made during the early 1970s and the prolonged drought in the West African Sahel, when he suggested that “the desert has moved to within 100 miles of Beijing, and in the long term this desertification will have serious effects on food scarcity and people’s health and will force people to migrate” (D’Aleo, 2000). He also suggested that the desertlike condition was approaching Beijing at a rate of 1.2 miles per year.

The Chinese government has become increasingly concerned about another sign of desertification – the enhanced frequency and intensity of dust storms originating in its western provinces and blanketing the nation’s capital, Beijing (Royston, 2001), as well as dust storms originating in northern China. The government is especially intent on arresting such dust storms in advance of the 2008 Olympics to which they are hosts.

Under specific circumstances, desertification is totally irreversable. For example, in mountainous areas of West Africa, once the higher elevations are denuded of soil (wind and water erosion), it will require millions of years to reform. Former sand dunes, now vegetated, if deprived of that protection, will be remobilized, and desert dune encroachment will result. Those desert sands cannot be easily stabilized, nor made fertile (Fairbridge, 1968, p. 1134 et seq.). Examples can be seen in Senegal, Maci, Niger, Sudan, as well as in India and Australia.

Desertification: why does it occur?

Ever since the mid-1970s, researchers have been divided over whether to blame the climate system or human activities for desertification. Some researchers consider climate to be the major contributor to desertification processes, with human factors playing a relatively minor supporting role. Other researchers reverse the significance of these two factors. For example, Le Houérou (1959) concluded that “on its edges the Sahara is mainly made by man; climate being only a supporting factor” (quoted in Rapp, 1974, p. 32). A third group blames climate and humans more or less equally. For example, Grove (1974, p. 137) has noted that “desertification or desert encroachment can result from a change in climate or from human action and it is often difficult to distinguish between the two”. Each of these views can be shown to be valid, at least at the local level and on a case-by-case basis. Thus, there is a region-specific bias to perceptions about desertification, one that spills over to the definitions.

Climate

References to climate in these definitions relate either to interannual climate variability, climate fluctuations, climate change, or drought. *Climate variability* (a term that is usually overlooked in these definitions) refers to the natural variations that appear in the atmospheric statistics for a designated period of time, usually on the order of months to years. Variations can occur in any or all of the atmospheric variables (such as precipitation, temperature, wind speed and direction, relative humidity, evaporation, etc.). Those variations could alter an ecosystem, which would eventually affect human activities in adverse ways, activities that had been designed to exploit the productivity of that ecosystem.

It is important to note that during the annual dry season the characteristics of the atmosphere in an arid or semiarid area are like that of a desertlike region (low precipitation, high evaporation, high solar radiation, etc.), and if the land is improperly used during this period, degradation results (Aubreville, 1949). Thus, short-term variations in climatic factors as well as seasonal dry periods, when combined with improper land-use practices, can give the appearance of the impact of a regional climate change (e.g. global warming) when none may have occurred at all. *Climate fluctuation* refers to variations in climate conditions that occur on the order of decades. Climate and hydrologic regimes are known to fluctuate between extended wet and dry periods that can last up to several decades. *Climate change* refers to the view that the statistics that represent the average state of the weather for a relatively longer period of time are changing, and that desertification is primarily the result of such natural climate change. For example, there has been an obvious multidecadal trend beginning in the late 1960s toward increased aridity in the West African Sahel; a natural desiccation of the region that humans can do nothing to stop. Usually cited as evidence for long-term climate changes in that area in the past are the fossil dune fields near the West African coast far from the active dunes close to the desert. The debate over the possible impacts of long-term global climate change on the climate conditions in the West African Sahel (and on other arid lands around the globe) continues.

Nevertheless, paleoclimatologists, point out that since the “Little Ice age”, which reached its nadir in the 17th century, there has been a systematic global warming (of natural causes), associated with aridification of the Sahara and other high pressure belts.

Drought episodes are also considered to be a major cause of high-pressure desertification. Especially during multiyear meteorological droughts, desertification becomes relatively severe, widespread, as well as more visible, and its rate of development increases sharply (e.g. Grainger, 1984). As the probability of drought increases as one moves from the humid to the more arid regions under present-day global climate conditions, so too, does the likelihood of severe desertification. Land forms, soils, and vegetation are often transformed, sometimes irreversibly, during such extended drought periods.

Tree-ring analysis, lake sedimentation, Nile floods and other proxies prove conclusively that drought cycles have been recurrent for at least the last few thousand years. Man-made pollution (CO_2), however, has amplified the late 20th century and early 21st centuary intervals.

The view held by the general public of what constitutes climate change exposes a misunderstanding. It is not just a matter of a summer warmer than last year, or less snow in winter than in the preceding decade. Scientists are referring to a profound climate change (a global warming of a few degrees Celsius), the magnitude of which societies have not witnessed for millennia. For reasons of clarity for the public, this profound type of change might be called "deep climate change". Many countries are now concerned about the possible impacts of global warming of the atmosphere on the rate and irreversibility, as well as the location, of desertification processes in future decades (Ci et al., 2002).

Human activities

Cultivation, herding, and wood-gathering practices, as well as the use of technology and even the occurrence of conflict (Timberlake and Tinker, 1984), have been cited in the definitions as major causes of, or contributors to, the desertification process in arid, semiarid, and, subhumid areas (e.g. Swedish Red Cross, 1984). *Cultivation practices* that can lead to desertification include irrigation, land clearing, deforestation, cultivation of marginal climatic regions, cultivation of poor soils, woodcutting for firewood and construction, and inappropriate cultivation tactics such as reduced fallow time, improper tillage, drainage, and water use. Areas that might support agriculture on a short-term basis may be unable to do so on a long-term sustained basis. Even land surfaces that are considered suitable for cultivation of some sort may become degraded, if they are managed in a way that is inappropriate to their ecological and climatic setting.

Rangeland abuse leading to desertification includes excessively large herds in relation to existing range conditions (e.g. overgrazing and trampling) and herd concentration around human settlements and watering points. Government policies toward their pastoral populations can also indirectly lead to desertification by, for example, not pursuing payment policies that encourage herders to cull their herds, by arbitrarily putting a minimum sale price on grain and a ceiling on prices that pastoralists might receive for their livestock, and so forth.

Gathering firewood by itself or in combination with overgrazing or inappropriate cultivation practices can create conditions that expose the land to existing "otherwise benign" meteorological factors (such as wind, evaporation, precipitation runoff, solar radiation on bare soil, etc.), thereby contributing to desertification.

The *use of technology* in arid, semiarid, and subhumid environments is often a result of the policy-makers' desire for economic growth and development. Thus, deep wells, irrigation and cash crop schemes, even the reduction of livestock diseases, each in its own way, increases the risks of desertification processes, if the technology is not properly applied. Desertification can result from road building, industrial construction, geological surveys, ore mining, settlement construction, irrigation facilities, and motor transport (Rozanov, 1977).

In sum, most researchers accept that both human intervention and climate are involved in the desertification process, with a few observers noting that the two factors are so entwined that to separate them as to primary and secondary contributors would be a fruitless endeavor.

Return to Aubreville

Aubreville discussed desertification at great length in his 1949 report entitled *Climats, Forets et Desertification de l'Afrique Tropicale*. His work, when compared to the scores of contemporary definitions, raises the issue about *where* desertification can take place. Most of the contemporary definitions relate desertification to what broadly speaking might be viewed as the desert fringes: the arid, semiarid, and dry subhumid areas. Aubreville explicitly referred to the dry tropical forest of Africa, noting that "these are real deserts that are being born today, under our eyes, in the regions where the annual rainfall is from 700 mm to 1500 mm" (1949, p. 332). Interestingly, Aubreville's original view of desertification would likely have no place in desertification studies today because it fails to meet the criteria identified in most contemporary definitions.

Aubreville viewed desertification primarily as a process but also referred to it as an event. He described how forested regions were transformed into savanna and savanna into desertlike regions. One of Aubreville's central concerns was the rate of destruction, resulting from human activities, of Africa's dry tropical forests. He noted that cultivation, deforestation, and erosion were so entwined as to lead to the destruction of the vegetative cover and soils in the forested regions of tropical Africa where "the desert always menaces, more or less evident, but it is always present in the embryonic state, during the dry and hot season" (Aubreville, 1949, p. 331). Savanna would result. Continued disregard for the fragility of the savanna would result in the creation of desert-like conditions.

Aubreville's original research findings and observations are still relevant to contemporary efforts to identify, understand, and combat desertification processes. The resurrection of his research on desertification is not a call to discard other definitions, but a call to broaden thinking about what constitutes desertification as a process and where on Earth that process might occur. If desertification can be identified by some of its component subprocesses, such as soil erosion, deforestation, overgrazing, or cultivation in marginal areas as defined, for example, by soil characteristics or by the amount of rainfall, then there is a great deal of research activity under way that relates directly as well as indirectly to desertification, even though the word desertification does not appear in its title (e.g. Riquer, 1982).

A broad view of desertification would shed a different light on progress in the understanding and combating of desertification. There is much research under way on soil erosion, range management, deforestation, increasing biological productivity in arid and semiarid lands. Only in this broader conceptualization of desertification can we develop a more accurate assessment of how nations are really doing in their national "war" against desertification.

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Cross-references

Arid Climates
Aridity Indexes
Deserts
Drought

DESERTS

The world's deserts are some of its most extreme and spectacular environments. The incredible dune systems of the Sahara or the Namib are but two examples; the bountiful succulents fields of the American southwest are another. Desert environments globally are highly diverse, a result of the complexity of the climatic conditions that can produce aridity and the underlying surface materials. However, all deserts share one essential commonality: a relatively scarcity of precipitation.

The definition of a desert depends on the aspect of environment of principal concern, such as vegetation, terrain, culture, climate or resources; hence there is no simple way to define or delineate desert environments. Even climatic boundaries of deserts, and therefore geographic boundaries, are hard to establish because there is a gradual and continual transition between arid and semiarid environments.

In basic climatic terms a desert can be defined as an area which receives little or no rainfall and experiences no season of the year in which rain regularly occurs. However, rainfall alone insufficiently defines climatic boundaries of deserts because it varies dramatically from year to year and because aridity is not determined solely by rainfall. What distinguishes deserts from non-deserts is the amount of moisture available to the ecosystem, or the difference between the rainfall a region receives and that lost through evaporation. According to estimates based on this concept, true deserts make up roughly 20% of the Earth's land surface and another 15% is semiarid.

Deserts are concentrated in Asia, Africa, and Australia. The largest expanse of arid land lies in an almost continuous area stretching nearly half a hemisphere across northern Africa and Asia, an inhospitable barrier separating most of Europe from southeastern Asia. Africa and Asia respectively contain 37% and 34% of the world's arid lands. The principal deserts of the world include (see Figure D4) the Kalahari–Namib, Somali–Chalbi and Sahara on the African continent; the Arabian, Iranian and Turkestan Deserts of the Middle East; the Thar, Takla-Makan and Gobi Deserts of Asia; the Monte–Patagonian and Atacama–Peruvian Deserts of South America; the Australian Desert; and the North American Desert, including the Great Basin and the Sonoran, Mojave and Chihuahuan Deserts. Vast tracts of semiarid land, such as the American Great Plains and the African Sahel, border each of these.

The deserts shown in Figure D4 tend to be situated in subtropical latitudes or in the lee of major mountain ranges, as the factors which promote aridity are common to these locations. Deserts are also found at high altitudes and high latitudes, but these differ in two basic respects: the low rainfall is primarily a result of cold conditions and evapotranspiration is inherently low and of minor importance in determining water availability.

Classification of deserts

Although sparse or negligible rainfall is a common characteristic of all deserts, aridity is better defined by moisture availability. This a residual in the balance between water availability through precipitation and water loss via evapotranspiration. The latter quantity represents the maximum amount of water that could be evaporated by solar energy or transpired by plants under conditions of constant moisture supply. Potential evapotranspiration can be as high as 3000 mm in some regions. In deserts, however, water is limited and hence this maximum is never achieved. Nevertheless, this parameter can be considered as "water demand" and climatic characteristics such as temperature or incoming radiation are used to approximate this demand. Rainfall, in turn, represents water availability.

Water demand, whether assessed by net radiation, temperature or potential evapotranspiration, varies greatly from one region to another. It tends to decrease with increasing latitude and it is higher in summer than winter. Therefore the amount of rainfall at the desert margin tends to decrease with increasing latitude, and it is higher for deserts with summer rainfall. Within a geographical region, water demand is more constant and desert boundaries are often delineated regionally on the basis of mean annual rainfall. In Australia, for example, the generally accepted limit for the desert is 400–500 mm of rainfall in the north and 250 mm in the more temperate climate of the southern border.

A comparison between supply and demand forms the basis of most definitions of deserts. All systems of assessments are in reasonable agreement on global space scales, but show significant differences along the margins at regional scale. The best-known

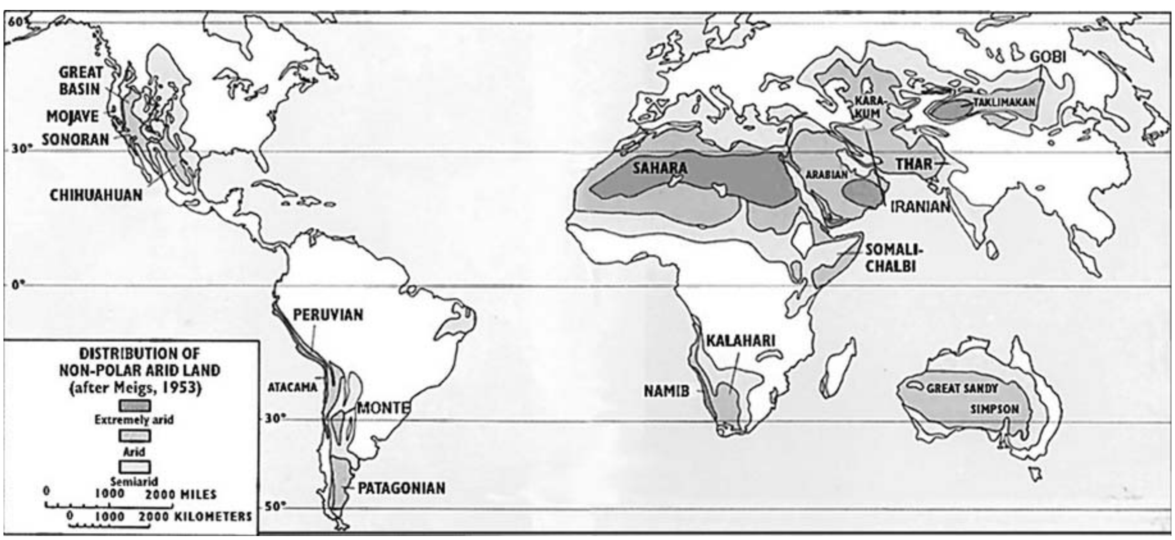

Figure D4 Location of the world's major deserts, according to Meig's classification.

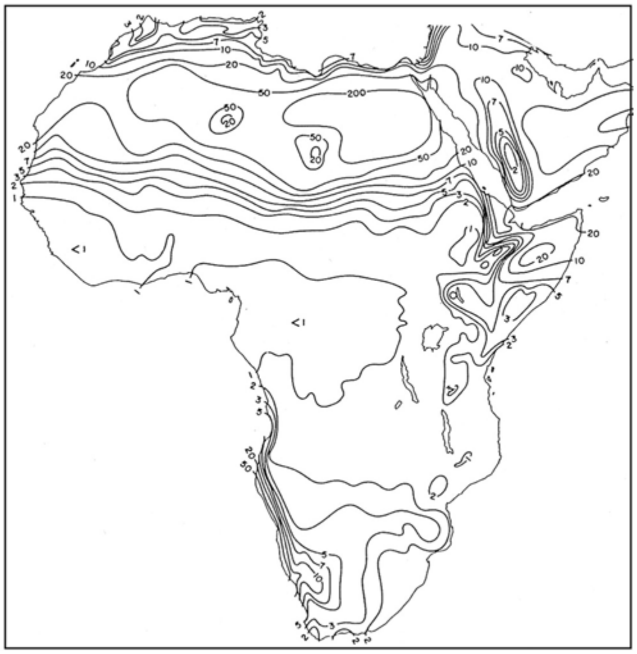

Figure D5 Budyko's radiational index of dryness over Africa.

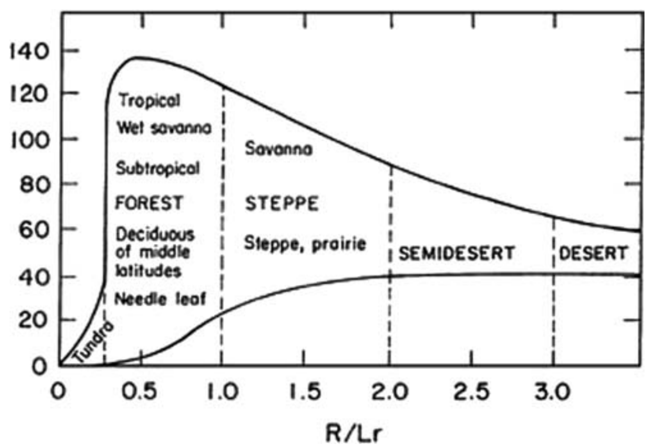

Figure D6 Budyko's concept of geobotanical zonality: the principal ecosystems as a function of net radiation and the dryness ratio (ratio between annual net radiation and annual average precipitation multiplied by the latent heat of condensation).

classification scheme for arid lands, that of Peveril Meigs, assesses "demand" by way of potential evapotranspiration. An example of Meigs' classification for Africa is shown in Figure D4. The classification scheme of the Russian climatologist Budyko represents it by the net radiation received at some location, i.e. the difference between the net heat gain from the sun and the net heat loss by radiation from the ground (Figure D5).

The Budyko classification has some advantages, in that it allows for a simple quantitative comparison of the degree of aridity of various deserts and its aridity index is readily interpreted physically. The index is a parameter termed the "dryness ratio". To produce it, net radiation is converted to energy units and the index is defined as the ratio of mean annual rainfall to the amount of rainfall which this energy suffices to evaporate. In Budyko's classification the boundary between deserts and semiarid regions is where the ratio is 3 (Figure D6). This ratio is as high as 200 in the central Sahara, but is generally below 10 in the North American deserts.

Causes of aridity

The formation of rainfall requires moisture supply, unstable atmospheric conditions and ascending air. Ascent can be produced by extreme heating of the surface, by a convergent pattern of air flow, or orographically forced by mountain barriers. Aridity is promoted by the opposite conditions: a lack of atmospheric moisture, stable air, subsidence (i.e. descending air motion), and a divergent pattern of air flow (i.e. air streams spreading apart from each other). Another cause is distance from the main tracks of major weather systems.

Except in polar and high-altitude deserts, a lack of sufficient moisture is generally not the overriding cause of the arid climate. The case of the Sahara Desert clearly demonstrates this. In summer the atmosphere above the Sahara is enriched with about as much moisture as that over the wetter regions of the southeastern United States. Likewise, the Namib Desert of southwestern Africa is a very humid environment, although it is one of the driest (i.e. most rainless) deserts on Earth.

The other factors, stable and subsiding air and divergent flow, are common to two meteorological situations linked to the occurrence of dry climates: the semipermanent high-pressure systems which prevail in the subtropical latitudes and the rainshadows on the leeward sides of mountain barriers. These are the most common locations of deserts.

Descending currents are particularly effective in promoting aridity. They originate at high altitudes, where the air is dry and, as they sink, they undergo intense compressional heating. Consequently, the air is very hot and dry when it reaches the surface. The warming also produces a temperature inversion (temperature increasing with elevation), which stabilizes the lower atmosphere and suppresses the uplift required to produce clouds and precipitation. Air descends in the core of high-pressure cells because of the pattern of surface air flow; it descends also in the lee of mountains.

Near the high-pressure cells, aridity is further enhanced by a temperature inversion produced by the descending air and by cold water on the eastern flanks of the highs. The occurrence of this unusually cold water is linked to the surface wind flow around the high, which produces the upwelling of cold water and advects cold polar water into relatively low latitudes. Along the coast of South America the upwelled water is as cold as 12°C, compared to over 20°C in the mid-ocean.

Both the subtropical highs and mountain barriers further promote aridity by blocking the passage of major weather systems. Mountain barriers also act as a barrier to the inland penetration of moist, maritime airmasses. The transformation of airmasses crossing the mountains produces a "rainshadow". Air approaching a mountain range is forced to rise, promoting cloud formation and rainfall on the windward side and the peaks. The air which reaches the leeward side has dropped its moisture at higher elevations and is relatively dry. As it sinks in the lee, compressional heating accentuates its dryness.

Most of the world's largest deserts are under the influence of the subtropical highs: the Australian Desert, the Peruvian–Atacama Desert of South America, the southwestern United States, the Namib Desert and Kalahari of southern Africa, and the Sahara. Aridity is strongest on the western sides of continents in these latitudes, where the influence of the highs is greatest and where the coastal deserts lie.

The deserts of the midlatitudes are generally located in the lee of major mountain ranges: the Patagonian Desert of South America, many of the deserts of the Middle East and Asia, and the intermontane region of the western United States. Topography also plays a role in the Somali–Chalbi Desert of Ethiopia and the Horn of Africa and, to some extent, the Thar desert of India.

In most cases, however, complementary factors also play a role in producing aridity. For example, the influence of the subtropical highs cannot suffice to explain the full extent of the Sahara and its continuation into Arabia and the Middle East. There, neither the cold-season temperate latitude weather systems to the north nor the warm-season tropical disturbances on its equatorward side penetrate to its interior. The deserts of Asia and the Middle East are far from prevailing storm tracks. The latter two regions are also quite distant from any moisture sources. In the Somali-Cholbi Desert, one factor is local patterns of wind flow, jet streams lying near the surface. A coastal, low-level jet stream enhances the aridity of the Peruvian Desert, the most latitudinally extensive desert in the world.

Thus, the causes of desert climates are quite complex and often regional influences must be taken into account. The complexity and the regionalization of these factors gives a nearly unique climatic identity to each of the Earth's major dryland regions, despite their many common climatic characteristics.

Surface environments of the desert

The vision of the sandy desert is applicable to only a portion of the world's arid lands. Other surface types include bedrock (often termed hammada), stone pavements (termed reg and serir), depositional flats, and desert crusts. Sand fields and dunes are common in the Sahara and in parts of the Australian Desert, but the Syrian and Gobi deserts are largely hammada and reg types. As the desert gives way to semiarid landscape, soils become more common and widespread.

Overall sand dunes occupy less than 20% of the surface area of the world's deserts. They cover about 28% of the Sahara but only 1% of the desert surface in North America. Classically, two types of dunes are distinguished: longitudinal (or linear) dunes, which are roughly parallel to the prevailing winds, and transverse dunes, which are aligned roughly normal to the wind. In reality, a great variety and complexity of dune forms exist. The simpler dune forms result from simple wind regimes, i.e. one or two prevailing directions. As the complexity of the prevailing winds increases, so does the complexity of dunes.

Many deserts sustain a rich vegetation cover, which can include grasses, trees and shrubs (although fewer in number than in the wetter environments). In the true deserts arboreal species (trees and tall shrubs) are rare, as are perennial grasses. The dominant vegetation in most deserts includes dwarf shrubs and low shrubs (such as *Artemisia* or sagebrush) and succulents (cacti and euphorbia). Annual grasses may be present in the years with abnormally high rainfall.

Desert vegetation consists of two general classes, based on the primary way to resist moisture stress: perennials which *avoid* drought, and annuals or ephemerals, which *evade* it. The latter grow profusely during periods of favorable precipitation and produce seeds which lie dormant during drier episodes, until wetter conditions return. The perennials are phreatophytes, which develop long taproots penetrating downward to the water table, or xerophytes, which adapt to low water supply and high salinity. The xerophytes include many dwarfed, woody species, with reduced water demand, and succulents, that resist drought by storing water in their leaves, roots and stems. The succulents include the cacti of the American deserts and the Old World euphorbia.

Diversity and extremes of desert climates

Most desert environments share several common climatic characteristics. These include meager rainfall which is highly variable in time and space, and often concentrated in very small, localized areas; low atmospheric relative humidity; an extreme thermal environment with large fluctuations of temperature between day and night and during the year; and generally low cloudiness and high insolation. Individual deserts differ markedly with respect to the amount of rainfall and the degree of aridity. The thermal characteristics, especially mean annual temperature and its seasonal variations, are determined to a large extent by latitude.

Consequently, several types of deserts are distinguished on the basis of climate: warm, cold-winter and foggy or coastal deserts (Figure D7). In the warm deserts of the lower latitudes, temperatures are high year-round and freezing is rare or absent. These may occasionally receive incursions of frigid air from higher latitudes, producing frost or even snow. The midlatitude deserts generally experience cold winters, often with seasonally occurring freezing temperatures. Both are characterized by low relative humidity year-round.

In contrast, coastal deserts are relatively humid and the temperatures relatively mild in both winter and summer, a consequence of the influence of the coastal waters. Compared to inland deserts, both the diurnal and annual temperature ranges are reduced. Also, they tend to be frequently cloud-covered and fog is a common occurrence.

The rainfall conditions in deserts are quite diverse. Some, such as the Sahara, have virtually rainless sectors with less than 10 mm of rainfall annually. Rainless stretches of 10 years have been recorded in in parts of the Sahara and at locations such as Swakopmund (Namibia) and Lima (Peru) in the coastal deserts of Southern Africa and South America. Few deserts are this dry. In the Sonoran, Mojave, Iran and Arabian Deserts and in the Takla-Makan, mean annual rainfall is on the order of tens of millimeters in their driest cores. It exceeds 80–100 mm everywhere in the Thar, Gobi, Patagonian and Australian Deserts and in the Kalahari. In contrast, it scarcely falls below 200 mm in the Chihuahuan Desert and Great Basin of North America.

The temperature conditions are also diverse because they depend on several factors, including latitude, elevation, distance from coast and degree of aridity (Figure D8). Except in coastal deserts mean daily maximum temperatures during the summer months are generally on the order of 30–45°C. The mean daily winter minima are usually above −10°C, except in the interior of Asia, where they may be as low as −20 or −30°C. There is a general tendency for annual temperature

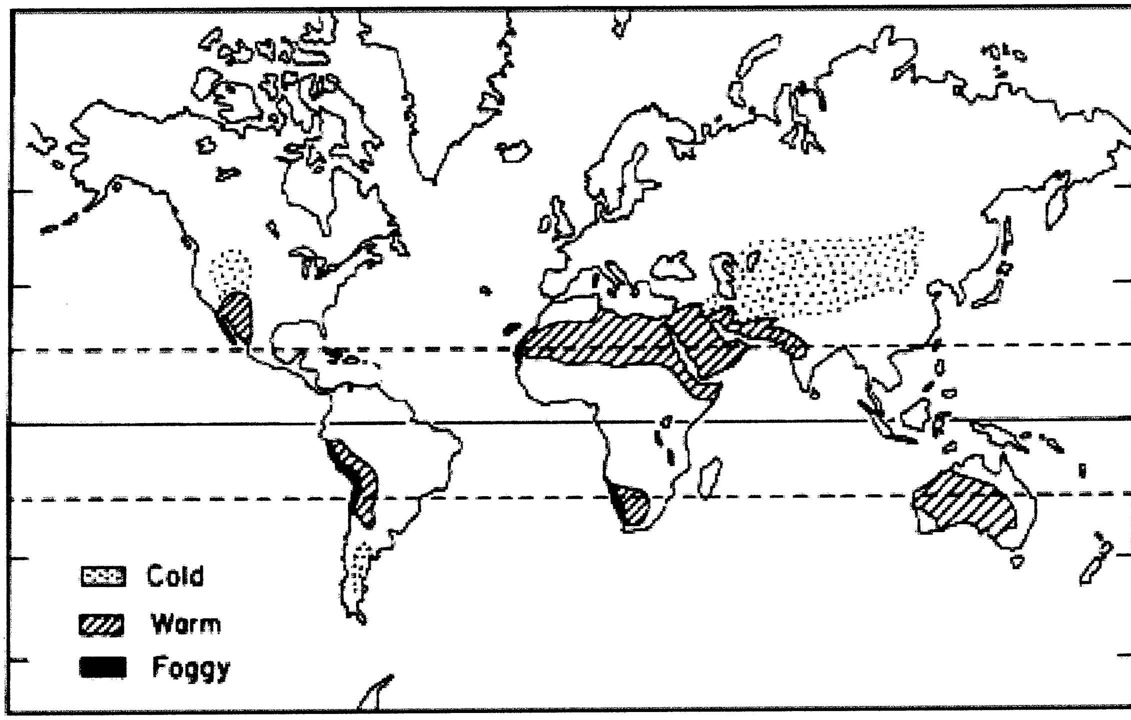

Figure D7 Classification of desert regions into cold, warm and foggy deserts (after Schmida).

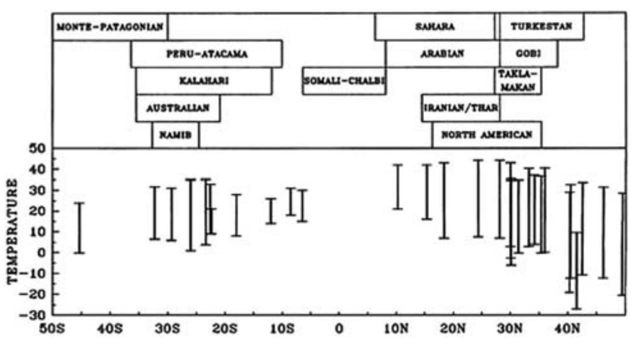

Figure D8 Annual temperature range vs. latitude for arid and semiarid regions. Bars extend from mean temperature of the warmest month to mean temperature of the coldest month. Note the smaller temperature range in the southern hemisphere, a consequence of the large ratio of water to land.

range to increase with latitude, varying from about 15°C in low-latitude deserts to 20–35°C in the cold-winter deserts. The mean diurnal range is likewise diverse, varying from about 4°C in coastal deserts to 22°C in high latitudes.

These mean conditions of rainfall and temperature do not fully illustrate the extreme range of thermal conditions experienced in deserts. In Australia and Asia the absolute maximum air temperatures are on the order of 48–50°C, but temperatures of 57°C and 58°C have been recorded in the Sahara, 57°C at Death Valley, California. Surface temperature commonly fluctuates by over 30°C between day and night in the Kara Kum Desert of Asia and by over 40°C in the parts of the North American Deserts. Some deserts of the Soviet Union experience absolute temperature ranges in excess of over 100°C, with air temperatures as low as −58°C having been recorded.

Ground temperatures are even more extreme, with temperatures in excess of 70°C having been recorded at several locations. At Port Sudan on the Red Sea, a sand temperature of 83.5°C was recorded. The deserts also experience extreme cold: at Repetek, in the Kara Kum desert of Asia, where a sand temperature of 79.4°C was once recorded, the ground temperature can drop to about −40°C.

The precipitation regime is similarly extreme. In some areas many years pass without a drop of rain, but when rain does fall it is often torrential. Many times the mean annual rainfall can fall within hours or days. At Lima, where the mean annual rainfall is 46 mm, 1524 mm fell during one storm in 1925. In the Sahara at Nouakchott (Mauritania), over twice the annual mean, 249 mm, fell in 1 day; at Tamanrasset (Algeria), the mean annual rainfall of 48 mm once fell in hour.

Thermal regime

The subtropical location of many deserts and the scant cloud cover of most produce a regime of strong solar insolation and high surface temperatures. Temperature is enhanced by the dryness of the soil and the lack of a dense vegetation cover to absorb and redistribute the solar radiation near the ground. The heat is concentrated at the surface because the dry ground transports little heat to deeper layers of soils; temperature decreases rapidly with depth into the ground and with height above the

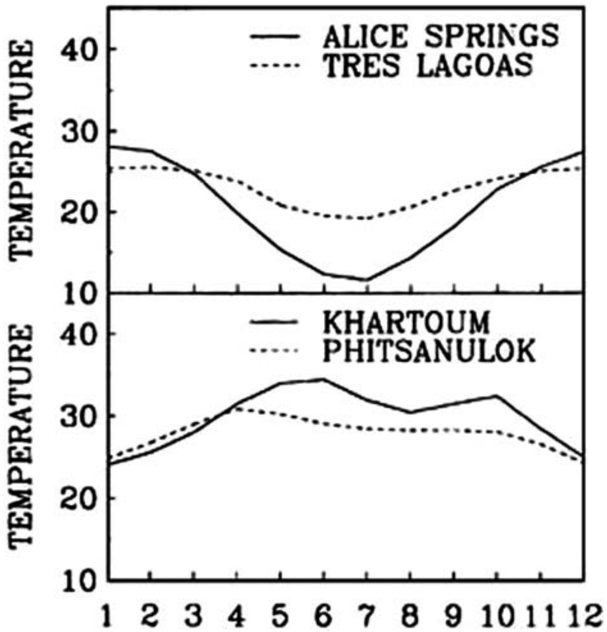

Figure D9 Mean monthly temperature at pairs of stations at comparable latitudes but differing precipitation regimes. Alice Springs and Khartoum are desert locations; Tres Lagoas and Phitsanulok are regions of tropical forests.

surface. In the Kara Kum Desert of Asia daytime temperature typically drops over 15°C within the first few centimeters and 20–30°C within the first 10 cm below the surface. Air temperature can drop by more than 10°C within the first 10 cm above the surface.

The concentration of heat at the surface means that there is no subsurface thermal reservoir. As a consequence of this, and the sparse vegetation cover, the surface cools extremely rapidly and efficiently at night. The generally clear skies and the dryness of the air near the ground allow most of the heat accumulated by day to escape to the upper atmosphere by night (90%, compared to 50% in humid regions). This accentuates the nighttime cooling.

The result is a large daily range of both ground and air temperature. At Khartoum, Sudan, at 15°N latitude in the eastern Sahara, the daily air temperature range is on the order of 18°C in the dry season and 11°C in the wet season. At Alice Springs, at 23°S in central Australia, the diurnal range is about 15°C. The daily fluctuations at humid stations of comparable latitude would be about half as great during the wet season. At a station in the Sahara, during the course of a day the air temperature fell from a daytime maximum exceeding 37°C to −1°C at night. At Death Valley, California, a daily range of 41°C was observed in August 1891; at Tucson, Arizona, the record is 56°C.

The lack of a surface heat reservoir in deserts tends to lead also to a high annual range of temperature. To a large extent the annual range is dependent on latitude, increasing with latitude as seasonal contrasts become important. Nevertheless, the annual temperature range at a desert location will tend to be greater than that at a humid location at a comparable latitude. The annual ranges for Alice Springs (24°S) and Khartoum (16°N) are 16°C and 10°C respectively, compared with approximately 6°C at Tres Lagoas (Brazil) and Phitsanulok (Thailand), at similar latitudes but with humid climates (Figure D9). In deserts near the equator the annual range is often much less, so that the daily temperature range is several times larger than the annual range.

Hydrologic regime

Much of the hydrologic character of a desert is dependent on its latitudinal location. Tropical rainfall prevails at low latitudes, such as in the southern Sahara or the northern sector of the Australian Desert. A midlatitude rainfall regime prevails at higher latitudes, such as the poleward sectors of these deserts or in the deserts of North America and much of Asia. The tropical and midlatitude regimes differ with respect to both the nature and seasonality of the precipitation and, consequentially, with respect to the loss of moisture through runoff and evapotranspiration.

Tropical rainfall is produced by convective processes (i.e. cloud formation related to localized surface heating and dynamic processes). In the midlatitudes most rainfall (especially that which occurs in winter) is linked to large-scale warm or cold fronts. Convective rainfall tends to be much more localized and intense than frontal rainfall. As a result, in areas where convective rainfall prevails, whether deserts or humid regions, rainfall is highly variable in space, confined to raincells on the order of 10–50 km, or less. The monthly rainfall at two locations a few kilometers apart might be quite different. For this reason rainfall in deserts was often thought to be a completely random and localized occurrence. Satellites have shown, however, that although this is true of individual raincells, these cells tend to occur in organized, large-scale, meteorological disturbances.

Convective rainfall tends to be of both short duration and high intensity. A typical rain might last for a few minutes or hours, compared to days for frontal rainfall. The high intensity of the convective rainfall also affects its effectiveness, since the ground quickly becomes saturated and much of the rainfall is lost to runoff. Because there are few drainage channels in deserts, the runoff may form a thin sheet of water, transforming the barren ground to an enormous lake within minutes. This runoff produces flashflooding in many deserts, especially when rain falls over barren rock at higher elevations. As little as a few millimeters of rain can produce flow in dry desert wadis; the flow may emerge suddenly, peak rapidly, but last only a few hours. Less than 100 mm can produce catastrophic floods. In the Tadmait Plateau of the Sahara a rain of approximately 16 mm generated a flood with peak discharge of about 1600 m^3/s.

Not only the rainfall in individual storms, but also the mean distribution in a desert, can be a mosaic, particularly in the rainshadow deserts. In the state of Washington, in the western United States, mean annual rainfall varies from 3000 mm on the peaks of the Cascades to less than 200 mm in the leeside valleys only 40 km away. Isolated mountains, such as Tibesti or the Hoggar in the Sahara, dramatically enhance rainfall. Peaks may routinely receive 100 mm or more per year, compared to a few millimeters in the surrounding regions.

Although by some definitions a true desert is a location without a regular rainy season, in most desert regions there is a preference for concentration in either the warm or cool season (Figure D10). The subtropical deserts represent a transition

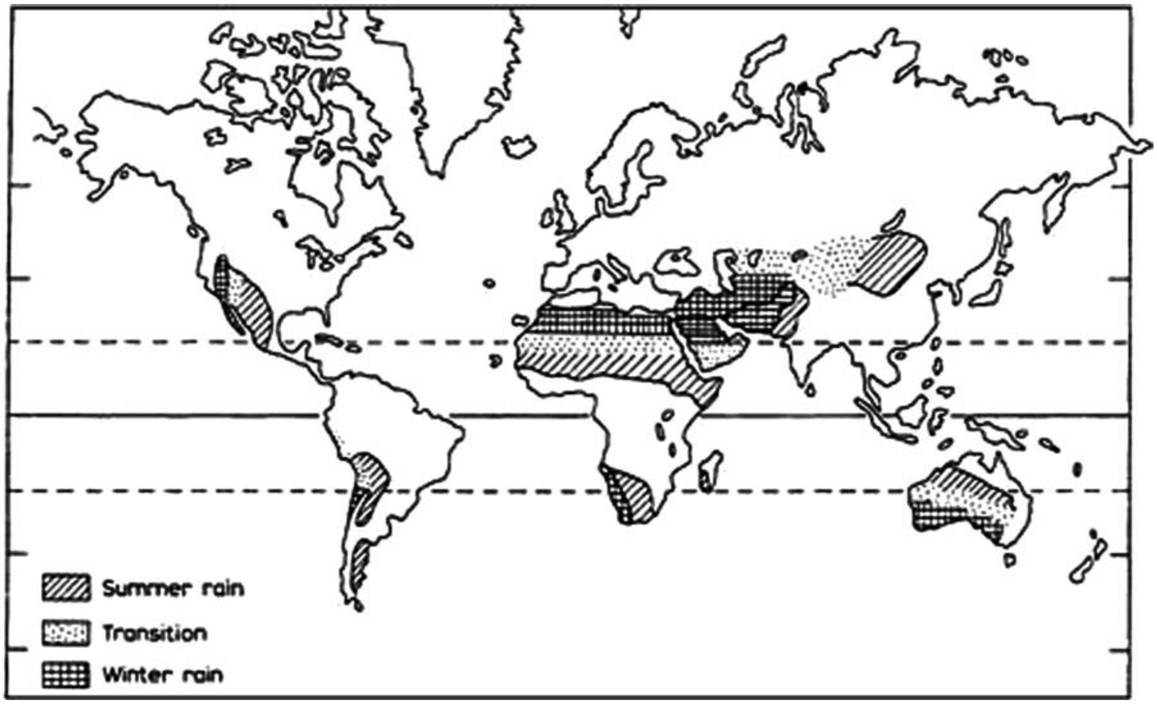

Figure D10 Areas of hot deserts with summer rain, winter rain and rainfall during the transition seasons (from Schmida).

Figure D11 Saguarro cactus in the Sonoran Desert of Arizona.

from tropical, summer rainfall, which prevails along their equatorward margins, to midlatitude, winter rainfall on their poleward borders. Both the seasonality and amount of rainfall decrease toward their center.

In the cold-winter deserts of the midlatitudes, fewer generalizations can be made about the seasonal occurrence of precipitation. For example, in the western Great Plains of the United States, precipitation is concentrated in summer, but the desert Southwest tends to receive both summer and winter rainfall, with greater aridity in the transition seasons. In some deserts of the Middle East the maximum is in spring. In most midlatitude deserts summer rainfall has the characteristics of tropical rain, falling in intense but brief bursts which promote high runoff. Winter rainfall is usually linked to large frontal systems, of low to moderate intensity but persisting for long periods.

For these reasons, and because potential evapotranspiration is higher in summer than winter, summer precipitation is less effective for vegetation growth. The seasonality of the meager precipitation can produce vastly different surface conditions. The Mojave Desert of California is distinguished from the adjacent Sonoran Desert of Arizona and northern Mexico on the basis of the percent of precipitation fall during the winter season. The latter is characterized by succulent vegetation, such as the giant saguarro cactus (Figure D11); while the former features dwarf shrubs and the uniquely-formed Joshua tree.

Snow occasionally falls in the poleward margins of the subtropical deserts. At oases such as Ouarghla and Ghardaia in the northern Sahara, snow falls as often as 1 in 10 years. At Laghouat snow fell nearly every year toward the end of the nineteenth century and now occurs every 2–5 years. The traditional housing is not meant to withstand such occurrences, which may lead to the collapse of roofs. In the higher latitudes snow is much more common, especially in deserts where precipitation is concentrated in the winter months. These include the Takla-Makan and Iranian Deserts.

The distribution of rainfall in a desert is erratic in both space and time, especially in regions of tropical rainfall. The amount of rainfall varies tremendously from year to year; many years may pass without a drop. Usually rain occurs only a few days within the year and most of the rain which falls occurs within short periods, sometimes as briefly as a few hours. Several times the mean annual rainfall may occur within one day. In Helwan (Egypt), where the mean annual rainfall is about 20 mm, seven storms produced a quarter of the rain that fell during an entire 20-year period. At Nouadibou (Mauritania), with mean annual rainfall of 32 mm, annual totals have ranged from 0 to 301 mm; on one day in 1909, 140 mm fell. At Biskra (Algeria) (mean annual rainfall of 140 mm), annual totals range from 32 to 638 mm, but 299 mm fell in September of 1969 (210 of it in 2 days). The same storm system brought nearly 800 mm to Sidi bou Zid (Tunisia) during September and October, months in which the mean rainfall is on the order of 10–20 mm.

Coastal deserts

Deserts are common along the western coasts of continents in the subtropical latitudes, where high pressure prevails. These deserts have certain climatic characteristics, such as a high frequency of fog, which distinguish them from other desert regions. Their origin lies in three main factors: the aridifying influence of the subtropical high-pressure cells over the oceans and adjacent coasts; the cold water which exists along these coasts; and a frictional effect of the shoreline on the coastal winds. Aridity is greatest at the coast, with rainfall increasing inland. Many local factors serve to accentuate the coastal aridity, such as near-surface jet streams constrained by coastal mountain chains.

The extent of the coastal deserts ranges from 25° of latitude for the Peruvian–Atacama Desert of western South America to less than 5° of latitude for western Australia. The latitude of their equatorward margin, with summer rainfall, is highly variant, but the poleward border with winter rainfall is in all cases at about 25°N or S of the equator. In those of Africa and South America, rainfall approaches zero in the arid core.

The climatic conditions of coastal deserts are less extreme than those of inland deserts. Many of the coastal deserts are relatively moist environments, with a high frequency of fog and relatively high atmospheric humidity. In some, more precipitation is received as fog-water than as rainfall. The temperature regime is generally quite moderate, as the water, with its high thermal capacity, dampens both diurnal and annual fluctuations. In the Namib, for example, the daily and annual range are about 6°C at the coast, compared to 15–20°C just 100 km inland.

These more moderate temperatures, together with the moisture provided by the fogs, create a more favorable environment for plants and animals than interior deserts. In the Peru–Atacama and Namib Deserts some plant and animal species have special adaptations which allow them to utilize fog-water. Certain plants can absorb water directly through the leaf surface. A species of beetle in the Namib builds trenches on the dunes to trap water as it condenses on the sand. Another "basks" on the dune with its head pointed downward and body to the wind, causing fog droplets to condense on its back and roll downward into its mouth.

Many coastal deserts are affected by a phenomenon called El a major change of temperature and wind patterns in the Pacific that has global climatic consequences. During El Niño years the cold water along the South America Desert coast disappears, establishing conditions which promote intense rainfall. In March and April of 1965 an El Niño brought 600 mm of rainfall to areas of coastal Peru, that receive on average about 80 mm during those months. The El Niño often renders similar changes along the coasts of Southern California, southwestern Africa and in other coastal deserts.

Winds, sand and dust

The desert surface conditions, barren ground and extreme heat, interact with the prevailing regional scale winds to produce a local wind regime which is strong and turbulent. The sparse vegetation cover means little surface friction to dissipate wind near the ground, so mean wind speeds are quite high in deserts. In the afternoon steady gale-force winds may prevail for hours, but at night, when the surface cools and the air becomes stable, winds are often calm. The desert winds are hot and dry and often blow from the desert to surrounding regions of more humid climate. Some, like the *Harmattan* of the Sahara, may provide welcome relief to stifling humidity.

The hot desert ground and rapid temperature drop above the ground produce unstable conditions which create gusty, turbulent winds. These are very effective in lifting particles from the surface. These winds are reflected in the patterns of sand dunes and surface erosion. They also produce sand and dust storms and smaller and shorter-lived dust devils. The heavy sand does not stay aloft very long, but the smaller dust particles do. The dust layer over the Sahara, for example, extends to over 5 km in altitude, producing vivid red colors in the clouds at this height.

When a dust storm occurs in a desert its effects can be instant and dramatic. Within minutes bright sunshine changes to an eerie, dusk-like ambience of red–brown haze and the temperature can drop more than 15°C. One particular type of dust storm, called a *haboob* in North Africa and the Southwestern United States, originates as a strong, turbulent downdraft in a thunderstorm. The dust is kicked up by what is called a density current, cold air which sinks to the ground from high altitude. As it hits the surface it spreads laterally, churning up dust in violent gusts that may exceed 60 mph. The visibility can rapidly approach zero, producing near darkness in mid-afternoon.

Microclimates in the desert

There are a number of microenvironments, or habitats, in deserts which offer shelter from the harsh conditions. It is here where life thrives. Some, such as parts of sand dunes and desert plants, modulate the thermal extremes. Others, such as oases and riverine environments, offer more favorable moisture conditions. Even dry riverbeds can support a virtual forest. Favorable habitats can also be dictated by topography or soils; the arid surface conditions are accentuated by stone pavements but moderated in lowlands near high relief. On the other hand, desert depressions, such as the Qattara depressions of Egypt or the Chott el Jerid of Tunisia, are the hottest places on Earth. The heat of the walls of the depression (Figure D12) creates a circulation cell of hot air that continues to heat up via conduction from the hot surfaces. At Tozeur, in the Chott el Jerid, the mean daily maximum temperature exceeds 42°C in June and July. In Death Valley, in the United States, the mean daily maximum exceeds 46°C in July.

Even an environment as small as a dune contains a number of microhabitats, as each part of the dune is affected differently by sun and wind. The side facing the morning sun will heat up first and by 8 a.m. may be 10°C warmer than elsewhere. In the afternoon the windy dune crest may be the

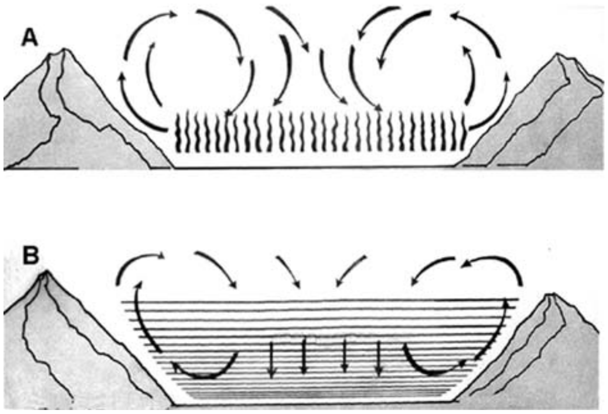

Figure D12 Heating of a desert depression.

Figure D13 The *Welwitschia*, an unusual plant of the Namib Desert, absorbs the fog water through its leaves. The long, flat, low surfaces of its leaves promote condensation.

coolest location by more than 10°C. Characteristic plant and animal communities reside at different parts of the dunes and in the interdune areas.

Water accumulates deep inside sand dunes, because the surface dries out first. This deep water reservoir helps to support plant life. Moisture also varies among the dune habitats. In coastal deserts, for example, where sea breezes bring fogs inland, moisture is most efficiently captured where wind is strongest.

Temperature and surface moisture are also moderated by plant cover. The temperature in litter underneath and within the leaves of a *Welwitschia* plant (Figures D13 and D14) may be as much as 20–30°C cooler than on the surrounding, exposed ground surface. The soil moisture content can be twice as high as in the exposed ground. Insects and small animals take refuge within the plant cover.

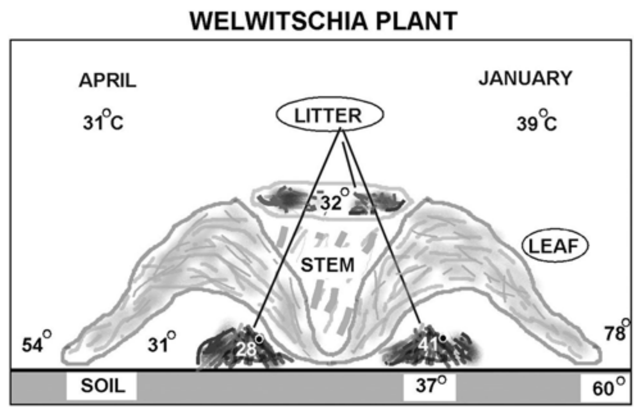

Figure D14 The relatively moderate microclimate of the *Welwitschia* plant provides a refuge for small animals and insects.

Climatic change

The Earth's deserts have undergone numerous climatic fluctuations on time scales of tens to tens of thousands of years. The fluctuations in these regions are roughly synchronous with major changes over the Earth as a whole. Those of higher latitudes have experienced fluctuations of both temperature and rainfall, but the major changes in the low-latitude deserts involve mainly rainfall. In recent times generally only the semiarid margins have been affected, but over the last 30 000 years the global extent of deserts has changed markedly.

During the last glacial maximum, about 18 000 years ago, the low-latitude deserts generally expanded, with the Sahara advancing nearly 10° toward the equator and its dunes overriding the lakes and rivers south of its previous border. The expansion of the arid zone into the tropics was so complete that the rainforests nearly vanished, their species taking refuge in a few highland habitats. At the same time "pluvial", or humid, conditions prevailed in many of the midlatitude deserts. Great lakes covered much of the current states of Utah, Nevada and California. Many dried up at the end of the Ice Age, about 10 000 years ago, and the left behind huge beds of fine sediments, like the Bonneville Salt Flats of Utah, where the ultra-smooth surface has permitted a vehicle to set a land-speed record of 622 mph.

The conditions which commenced about 10 000 years ago are in stark contrast, with a low latitude "pluvial" period reaching a maximum some 5000 years ago. Then, the low-latitude deserts were generally reduced to their hyperarid cores. There is little evidence anywhere of active sand dunes at that time. In parts of the Sahara, Neolithic man herded cattle and animals grazed on savanna vegetation; fish hooks uncovered in archeological sites attest to the presence of lakes in, and human occupation of, now-hyperarid regions.

A more recent period in which aridity has waxed and waned was around the Middle Ages, some 600–1200 years ago. Considered to be a global warm epoch, the core of this period was one of wetter conditions along the margins of many deserts. This was probably the case in the Peruvian Desert, the southwestern United States, Australia, the Mediterranean, the Middle East and the southern Sahara. Major civilizations, such as the Mali empire, thrived in presently semiarid regions of Africa. Caravan routes traversed now-waterless plains of the

Sahara and several towns flourished along these routes. On the other hand, drier conditions prevailed in some deserts and semi-desert regions of higher latitudes, such as the Great Plains of the central United States.

In recent centuries similar fluctuations of climate have affected desert regions, although less extreme. These are an inherent characteristic of the desert environment, and one to which life in the deserts has adapted. A quick look at the major deserts suggests no systematic change in recent decades, with one exception: throughout most of Africa there is a trend toward more arid conditions and expansion of the total area occupied by deserts. This is a significant percentage of the global arid environments and is cause for concern.

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Cross-references

Asia, Climate of Southwest
Desertification
Drought
Vegetation and Climate

DETERMINISM, CLIMATIC

Determinism is the doctrine that all happenings and existences are the inevitable outcome of a set of preexisting conditions, and specifically that human actions are not based on free will, but are determined by environmental influences. In its widest context such a philosophy is encompassed within the framework of environmental determinism. Climatic determinism is a subset of environmental determinism, with climate considered the major influence or control.

Environmental determinism has its roots in classical antiquity but in its modern terms can be traced to the influence of Charles Darwin, whose ideas made it inevitable that social scientists should see natural laws operating in the different cultures and activities of people. The formal statements of such a relationship are often attributed to Friedrich Ratzel (1844–1904), although many of the ideas presented in his work *Anthropogeographie* are not as naive as sometimes suggested by those who have referred to it. In the United States, Ellen C. Semple, a student of Ratzel's, became the foremost proponent of environmental determinism. Despite the avoidance of the word "determinism" in her work, she expressed her basic thesis in the declaration "man is a product of the earth's surface" (Semple, 1935).

Reaction to many of the simplifications of environmental determinism led other writers to proposed modifications of the role of environment in human endeavors. Thus "stop-and-go" determinism was proposed by Griffiths Taylor, who wrote:

> Man is able to accelerate, slow or stop the progress of a country's development. But he should not, if he is wise, depart from the direction as indicated by the natural environment. He is like the traffic controller in a large city who alters the rate and not the direction of progress (Taylor, 1955).

Similarly, the ideas of environmental possibilism and probabilism reflect a spectrum of the role of environment in determining the possible and probable outcome of human endeavors.

Within this flow of ideas it was to be expected that the role of climate as a significant part of the human environment should be given special emphasis. Climatic determinism has a developmental history of its own.

The early concepts

Variations from climatic conditions that existed in the heart of their world caused classical Greek philosophers and writers to postulate many ideas concerning the role of climate in the nature of people. In his discussion *On Airs, Waters and Places*, Hippocrates (*ca.* 420 BC) contrasted easy-going Asiatics with penurious Europeans by suggesting that the latter had to be much more active to ameliorate their environment. A similar theme occurs in the work of Aristotle (*ca.* 350 BC), who commented "The inhabitants of colder countries in Europe are brave but deficient in thoughts and technical skills" (see Tatham, 1957).

Such concepts were also used by Roman writers. Strabo (*ca.* 64 BC–AD 20), for example, suggested that the rise and strength of Rome was due in part to the climate, physical makeup, and position of Italy. With the decline of Rome, however, explanations of the role of humans in their environment diminished, and in medieval times writers were not encouraged to deal with items that did not completely conform to biblical teachings.

While this was true in the Christian world, Arabic writers did contribute to the climate–human relationship. The great historian–geographer Ibn Khaldun (1332–1406) divided the hemisphere into seven climatic zones. The extremes were uninhabitable and only the middle zone provided the climate in which people could excel in wisdom and were neither too stolid nor excessively passionate. He said that

> the human inhabitants of these zones are well proportioned in their bodies, color, character qualities and general conditions. The inhabitants of the zones that are far from temperate are also farther removed from being temperate in all their conditions. Thus the inhabitants of the middle zone have all the natural conditions necessary for a civilized life (Khaldun, 1958, vol. 1).

The sixteenth and seventeenth centuries produced writers who once again resurrected the classical ideas. Of particular note was the work of the French social writer Montesquieu (1689–1755). In his *The Spirit of Laws* he sought to determine the effects of climate and soils on the character of people and, in his opinion, climate was of particular importance.

Table D2 Selected concepts on climatic determinism

Author	Concepts
Hippocrates (*ca.* 420 BC)	Developed ideas on environmental influence on human behavior.
Aristotle (384–322 BC)	The varying habitability of the earth with differences of latitude: the inhabitants of extreme climate conditions are deficient in thought and technical skill, whereas living in the intermediate region combined the best quality of living.
Strabo (*ca.* 64 BC–AD 20)	Attempted to explain how climate affected the rise and strength of Rome.
Ibn Khaldun, A.R. (1332–1406)	Argued that environmental factors, such as climate, provide their due influence on such social factors as cohesion, occupation, and wealth.
Bodin, Jean (1530–1596)	Presented ideas of environmental influence on human life: the habitability of a place was a function of its latitude.
Carpenter, Nathanael (1589–1628)	Human character is determined by climate.
Montesquieu, Charles Louis de Secondat (1689–1755)	Presented ideas about the influence of climate on politics.
Kant, Immanuel (1724–1804)	Animals and men gradually change by their environment: effect of temperatures on nerves and veins, making the movements stiff and unsupple.
Von Humbolt, Alexander (1769–1859)	Developed the relations of latitude air, temperature, vegetation and agriculture in tropical mountains: made investigations with a view to seeking answers to questions about interconnections among the phenomena grouped together in rich diversity on the face of the Earth. He cautiously pointed out that atmospheric conditions merely favored that which had been called for by mental qualifications, and by the contact of highly gifted races with more civilized neighbors.
Ritter, Carl (1779–1859)	Some of his basic ideas concerning the influence of the Earth's major features on the course of history were developed. He sought to understand the interconnections, the causal interrelations, that make the areal associations cohesive. He was interested in the effect of the Earth on humans, the reciprocal action of humans on the Earth was to him equally significant.
Darwin, Charles (1809–1882)	Mechanism of natural selection of the cause of evolution, rather than need or use.
Spencer, Herbert (1820–1903)	Pointed out close resemblance of human societies to animal organisms.
Buckle, H.T. (1821–1862)	Physical agents have powerfully influenced the human race. These are climate, food, soil, and general aspects of nature. Contended that climate, generally working indirectly, is a major environmental influence.
Haeckel, E.H. (1834–1919)	Humans are only one of the organisms to be studied, and was equally in the grip of the surrounding forces; a proponent of Darwin's theory.
Ratzel, Friedrich (1844–1904)	The application of Darwin's biological concepts of human societies: human beings must struggle to survive in particular environments much as plant and animal organisms must do, known as Social Darwinism. He recognized climate as a chief environmental influence but pointed out that its effects are often indirect, affecting man by way of its influence on plants, animals, and soil.
Davis, William Morris (1850–1934)	Set forth his concept of geography as an explanatory description of the physical character of the Earth's surface, and of the human response to the physical surroundings. Began to seek cause and effect generalizations, usually between some elements of inorganic control and some elements of organic response. Attempted to bring cohesion to geography by introducing Spencer's ideas of Social Darwinism.
Demolins, Edmond (1852–1907)	Argued the role of climate produces grass vegetation; and the presence of grass determines a uniform mode of work – the art of pastrolism. Sought the "laws" which govern human actions.
Semple, Ellen Churchill (1863–1932)	Very careful to make the point that the environment does not control human activity: only that under certain circumstances there is a tendency for people to behave in predictable ways.
Dexter, E.G. (1868–1938)	Compared the daily temperature, atmospheric pressure, humidity, wind, sunshine, and precipitation in respect to the behavior condition investigated, and found statistically significant correlations between weather and conduct, suicide, and other crimes.
Patterson, S.O. (1868–1941)	Noted the human effects of the period of climatic instability that culminated the fourteenth century.

Table D2 (*Continued*)

Author	Concepts
Moore, H.L. (1869–1958)	Presented the idea of economic cycles as influenced by the climatic conditions.
Brunhes, Jean (1869–1930)	It is not influences that are sought but geographical relations between physical facts and human destinies; humans are creations of habit and habit once established becomes a part of their environment and exerts considerable influence on their later development.
Huntington, Ellsworth (1876–1947)	Refined the climatic hypothesis as related to climatic causation.
Bowman, Isaiah (1878–1950)	There is widespread evidence that there are climatic limits to profitable agricultural settlement in spite of the production of quicker maturing crops for hardier cattle.
Taylor, Griffith (1880–1963)	Humans are not free agents. If humans are wise they should not depart from the directions as indicated by the natural environment.
Visher, Stephen Sargent (1888–1967)	Of all the geographical influences to which humans are subjected. climate seems to be the most potent. Despite the fact that most climatic influences are “permissive”, “not deterministic”. various aspects of climate are so highly restrictive as to be in effect controls.
Toynbee, Arnold J. (1889–1975)	Was influenced by Huntington’s ideas about the relation between human beings and their physical environment; is not a determinist.
Mills, Clarence A. (1891–1974)	A professor of experimental medicine; he put forward many ideas in his book *Climate Makes the Man*, a title that expresses clearly his philosophy.
Markham, S.F. (1897–1975)	Related the relative

Accordingly, he noted that people who live in cold climates are stronger, more courageous, less suspicious and less cunning than those in hot climates, who tend to be like old men and are timorous, weak in body, indolent and passive. A similar theme was presented by the philosopher Immanual Kant (1724–1804), who also added that outside of temperate climes the inhabitants of both hot and cold lands were stiff and unsupple because too much or too little perspiration makes blood thick and viscous while too much heat and cold dry out nerves and veins.

Many other thinkers and writers, such as Ritter (1799–1859) and Humboldt (1767–1835) expressed opinions that, although more cautious, exhibited a similar outlook. Table D2, while far from complete, provides a list of writers who contributed toward the ideas of climatic determinism.

The twentieth century

The two names most closely associated with determinism in the twentieth century are Ellen Churchill Semple (1863–1932) and Ellsworth Huntington (1876–1947), with Semple being closely associated with environmental determinism in all its aspects and Huntington being best known as the archetypal climatic determinist. The work of Huntington is dealt with here.

Huntington’s early work was influenced by his travels in Asia and by James Geikie’s book *The Great Ice Age and its Relation to the Antiquity of Man*. Arising from these early influences was his book *The Pulse of Asia* (1907), in which he developed the idea that climate in postglacial time was becoming drier and that in Central Asia not only the habits but also the character of the people were molded by the environments resulting from climatic change. In effect, climatic change is one of the greatest factors in determining the course of human progress.

While continuing to work on climatic change, Huntington also developed the idea that there is a climatic optimum for the human being regardless of race or background. Studies on human productivity in New England led to the conclusion that temperature is the most significant variable and that the people in Bridgeport and New Haven are physically most active when the average temperature is between 60°F and 65°F, and mentally most active when outdoor temperature is about 38°F. Further, people do not work well when the temperature is fairly constant or extremely changeable. The ideal conditions are moderate changes, especially a cooling of the air at frequent intervals. These ideas were further developed in articles such as “The handicap of the tropics” (1913) and “The adaptability of the white man in tropical America” (1914).

These two main themes – climatic change and history and climate and the human response – are represented in much of Huntington’s further work. About the former, Martin (1973) has written:

> His bold scheme, imaginatively wrought, involving tree rings, lake levels, valley terraces, dunes, disappearing rivers, wilderness ruins and the whole apparatus for climatic change, was applied to history . . . it revealed an ever-changing climatic mileau explaining nomadic migrations, the fortunes of Kings, the downfalls of empires, outbursts of intellectual advance and lesser matters concerning rhythms.

His work on climate and human activities was marked by less scientific evidence and oversimplification of complex variables. Nonetheless, Huntington did recognize, long before it was popular, many aspects of applied climatology (see Fonaroff, 1965).

Current thought

There are few climatologists today who would admit to being climatic determinists. The sweeping generalizations, backed by minimal evidence, of Huntington and other writers cannot be accepted at face value. However, the extreme stance of determinists of the midtwentieth century led to a backlash effect in which climate and environment, when considered in any aspect of human activities, became an area of nonresearch. Voluntarism, the other end of the spectrum of thought, became viable.

Fortunately, other schools of thought, taking a midpath between the two extremes, were introduced and today a more rigorous approach to human–climatic relationships and the rise and fall of civilizations has again made it a respectable area of study.

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Cross-references

Climatic Change and Ancient Civilization
Crime and Climate
Cultural Climatology
Human Health and Climate

DEW/DEWPOINT

Dew is any water that is condensed onto the ground, rocks, grass, and so on. It generally forms at night due to radiational cooling (most effective on clear, still, cool nights), which causes the temperature of the air to fall below its dewpoint.

Dewpoint is the temperature at which saturation of the air occurs, i.e. the temperature at which the observed vapor pressure is equal to the saturation vapor pressure. If a parcel of air is hypothetically held at constant pressure and vapor content, the temperature at which it must be cooled to reach saturation is called its dewpoint or, if below 0°C, its frost point. Provided that any change in temperature of a parcel of air occurs without change in pressure or vapor content, the dewpoint will always be constant, i.e. conservative. On the other hand, if the parcel rises adiabatically, the dewpoint is quasi-conservative, because the dewpoint of moist air drops only at about one-fifth the rate of the dry adiabatic lapse rate.

A dewpoint hygrometer may be used to determine surface dewpoint. A refrigerated metal surface is brought in contact with air, causing condensation when it is slightly below the temperature of the thermodynamic dewpoint. More usually dewpoint is simply determined with a psychrometer (wet and dry bulb thermometers), used with appropriate tables (Table D3).

If the temperature is below freezing, hoar frost will form, but if the temperature drops below freezing *after* the dew has formed the result is white dew. Dew is especially effective when the ground layer of air has a high relative humidity, as along river valleys, near swamps, etc. Dew is often the only form of moisture available to plants and animals in extreme deserts.

An optical effect of dew is known as heiligenschein or Cellini's halo, brought about by an early-morning sun producing a shadow over the observer's head. Reflection from the dew-covered surface produces a "saintly" halo, said to have been described first by Cellini, who found it a divine sign.

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Cross-references

Humidity
Phase Changes

Table D3 Dewpoint temperature (1000 mb)

Dry-bulb temperature (°C)	Saturation vapor pressure (mb)	Wet-bulb depression ($T_d - T_w$)																					
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
−20	1.2540	−33																					
−18	1.4877	−28																					
−16	1.7597	−24																					
−14	2.0755	−21	−36																				
−12	2.4409	−18	−28																				
−10	2.8627	−14	−22																				
−8	3.3484	−12	−18	−29																			
−6	3.9061	−10	−14	−22																			
−4	4.5451	−7	−11	−17	−29																		
−2	5.2753	−5	−8	−13	−20																		
0	6.1078	−3	−6	−9	−15	−24																	
2	7.0547	−1	−3	−6	−11	−17																	
4	8.1294	1	−1	−4	−7	−11	−19																
6	9.3465	4	1	−1	−4	−7	−13	−21															
8	10.722	6	3	1	−2	−5	−9	14															
10	12.272	8	6	4	1	−2	−5	−9	−14	−28													
12	14.017	10	8	6	4	1	−2	−5	−9	−16													
14	15.977	12	11	9	6	4	1	−2	−5	−10	−17												
16	18.173	14	13	11	9	7	4	1	−1	−6	−10	17											
18	20.630	16	15	13	11	9	7	4	2	−2	−5	−10	−19										
20	23.373	19	17	15	14	12	10	7	4	2	−2	−5	−10	−19									
22	26.430	21	19	17	16	14	12	10	8	5	3	−1	−5	−10	−19								
24	29.831	23	21	20	18	16	14	12	10	8	6	2	−1	−5	−10	−18							
26	33.608	25	23	22	20	18	17	15	13	11	9	6	3	0	−4	−9	−18						
28	37.796	27	25	24	22	21	19	17	16	14	11	9	7	4	1	−3	−9	−16					
30	42.430	29	27	26	24	23	21	19	18	16	14	12	10	8	5	1	−2	−8	−15				
32	47.551	31	29	28	27	25	24	22	21	19	17	15	13	11	8	5	2	−2	−7	−14			
34	53.200	33	31	30	29	27	26	24	23	21	20	18	16	14	12	9	6	3	−1	−5	−12	−29	
36	59.422	35	33	32	31	29	28	27	25	24	22	20	19	17	15	13	10	7	4	0	−4	−10	
38	66.264	37	35	34	33	32	30	29	28	26	25	23	21	19	17	15	13	11	8	5	1	−3	−9
40	73.777	39	37	36	35	34	32	31	30	28	27	25	24	22	20	18	16	14	12	9	6	2	−2

DOLDRUMS

Doldrums are the calms of the Intertropical Convergence Zone. The regions are characterized by low atmospheric pressure, high humidity, and thunderstorms. They are often associated with the source of tropical hurricanes, the sites of water spouts, and windlessness, sometimes alternating with sharp squalls. They are not to be confused with the calms of the horse latitudes.

Doldrums is an old English word meaning an unpleasant, depressed feeling. According to the *Oxford English Dictionary* there apparently arose a misunderstanding of the phrase "in the doldrums" used by some sailors, the human physiological state or condition of being transferred to a geographic belt or locality. Maury in 1855 used the term in this sense, and the usage became widespread. The colloquial French for doldrums is *potau-noir*, literally the boot-polish jar. Figuratively, *être dans le pot-au-noir* means exactly "to be in the doldrums", hence the extension of the meaning to the equatorial calms later on. Most other European languages have no special name for these equatorial calms.

While the term doldrums is now seldom used in the literature, descriptions are common in older works. As pointed out by Brunt (1939), the doldrums are not by any means continuous throughout the year and do not form an uninterrupted equatorial belt. A sharp discontinuity occurs in the equatorial Pacific where the northeast and southeast trades meet; the latter rise over the former, accompanied by heavy rainfall. In the Pacific area, therefore, true doldrums only occur near the continental shores; while in the Atlantic they fluctuate both in width and in position (Durst, 1926).

Over the continents the equatorial belts are regions of calms and are subject to diurnal instability and thermal systems with heavier rainfall than over the oceans.

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Cross-references

Atmospheric Circulation, Global
Intertropical Convergence Zone
Trade Winds and the Trade Wind Inversion
Tropical Cyclones

DROUGHT

Drought is an insidious natural hazard that results from a deficiency of precipitation from expected or "normal" that, when extended over a season or longer period of time, is insufficient to meet the demands of human activities. As the world's population increases, societies are placing greater and greater pressure on finite water supplies and other limited natural resources – thus potentially increasing our vulnerability to extended periods of drought. In addition, growing concern over the impact of human activities on climate has heightened awareness of our sensitivity to climatic extremes such as drought. The results from scientific investigations indicate that the frequency and severity of drought may increase for some regions in the future as a direct result of increasing concentrations of greenhouse gases in the atmosphere.

Scores of definitions of drought exist, reflecting different climatic characteristics from region to region and sector-specific impacts. Although droughts are usually classified as meteorological, agricultural, hydrological, or socioeconomic, all types of drought originate from a deficiency of precipitation that results in water shortage for some activity or some group. Drought must be considered a relative, rather than absolute, condition. The ultimate results of these precipitation deficiencies are, at times, enormous economic and environmental impacts as well as personal hardship. Impacts of drought appear to be increasing in both developing and developed countries, a clear indication of nonsustainable development in many cases. Lessening the impacts of future drought events will require nations to pursue development of drought policies that emphasize a wide range of risk-management techniques, including improved monitoring and early-warning systems, preparedness plans, and appropriate mitigation actions and programs.

Drought concepts and definitions

Drought differs from other natural hazards in several ways. First, drought is a slow-onset, creeping natural hazard. Its effects often accumulate slowly over a considerable period of time and may linger for years after the termination of the event. Therefore, the onset and end of drought is difficult to determine. Because of this slow-onset characteristic it is difficult to recognize the onset of drought, and scientists and policy makers continue to debate the basis (i.e. criteria) for declaring an end to a drought. Second, the absence of a precise and universally accepted definition of drought adds to the confusion about whether or not a drought exists and, if it does, its degree of severity. Realistically, definitions of drought must be region- and application- (or impact-) specific. This is one explanation for the scores of definitions that have been developed. Third, drought impacts are nonstructural and spread over a larger geographical area than are damages that result from other natural hazards. Quantifying the impacts and providing disaster relief are far more difficult tasks for drought than they are for other natural hazards. These characteristics of drought have hindered the development of accurate, reliable, and timely estimates of severity and impacts and, ultimately, the formulation of drought preparedness plans.

Many people consider drought to be largely a natural or physical event. Like other natural hazards, drought has both a natural and social component. The risk associated with drought for any region is a product of both the region's exposure to the event (i.e. probability of occurrence at various severity levels) and the vulnerability of society to the event. The natural event (i.e. meteorological drought) is a result of the occurrence of persistent large-scale disruptions in the global circulation pattern of the atmosphere. Exposure to drought varies spatially and there is little, if anything, that we can do to alter drought occurrence. Vulnerability, on the other hand, is determined by social factors such as population changes, population shifts (regional and rural to urban), demographic characteristics, technology, government policies, environmental awareness, water-use trends, and social behavior. These factors change over time and thus vulnerability is likely to increase or decrease in response to these changes. Subsequent droughts in the same region will have different effects, even if they are identical in intensity, duration, and spatial characteristics, because societal characteristics will have changed.

Defining drought

Drought is the consequence of a natural reduction in the amount of precipitation received over an extended period of time, usually a season or more in length, although other climatic factors (such as high temperatures, high winds, and low relative humidity) are often associated with it in many regions of the world and can significantly aggravate the severity of the event. Drought is also related to the timing (i.e. principal season of occurrence, delays in the start of the rainy season, occurrence of rains in relation to principal crop growth stages) and the effectiveness of the rains (i.e. rainfall intensity, number of rainfall events). Thus, each drought event is unique in its climatic characteristics, spatial extent, and impacts. The area affected by drought is rarely static during the course of the event. As drought emerges and intensifies, its core area or epicenter shifts and its spatial extent expands and contracts throughout the duration of the event.

Because drought affects so many economic and social sectors, scores of definitions have been developed by a variety of disciplines. In addition, because drought occurs with varying frequency in nearly all regions of the globe, in all types of economic systems, and in developed and developing countries alike, the approaches taken to define it also reflect regional differences. Impacts also differ spatially and temporally, depending on the societal context of drought. A universal definition of drought is an unrealistic expectation.

Many disciplinary perspectives of drought exist, often causing considerable confusion about what constitutes a drought. Research has shown that the lack of a precise and objective definition in specific situations has been an obstacle to understanding drought, which has led to indecision and/or inaction on the part of managers, policy makers, and others. It must be accepted that the importance of drought lies in its impacts. Thus definitions should be region- and impact- or application-specific in order to be used in an operational mode by decision makers.

Drought is normally grouped by type as follows: meteorological, hydrological, agricultural, and socioeconomic. Meteorological drought is expressed solely on the basis of the degree of dryness (often in comparison to some normal or average amount) and the duration of the dry period. Thus, intensity and duration are the key characteristics of these definitions. Meteorological drought definitions must be considered as region-specific since the atmospheric conditions that result in deficiencies of precipitation are climate regime-dependent.

Agriculture is usually the first economic sector to be affected by drought because soil moisture supplies are often quickly depleted. Agricultural drought links various characteristics of meteorological drought to agricultural impacts, focusing on precipitation shortages, differences between actual and potential evapotranspiration, and soil water deficits. A plant's demand for water is dependent on prevailing weather conditions, biological characteristics of the specific plant, its stage of growth, and the physical and biological properties of the soil. A definition of agricultural drought should account for the variable susceptibility of crops at different stages of crop development.

Hydrological droughts are associated with the effects of periods of precipitation shortfall on surface or subsurface water supply (e.g. streamflow, reservoir and lake levels, groundwater) rather than with precipitation shortfalls. Hydrological droughts are usually out of phase or lag the occurrence of meteorological and agricultural droughts. More time elapses before precipitation deficiencies are detected in other components of the hydrological system (e.g. reservoirs, groundwater). As a result, impacts are out of phase with those in other economic sectors. Also, water in hydrological storage systems (e.g. reservoirs, rivers) is often used for multiple and competing purposes (e.g. power generation, flood control, irrigation, recreation), further complicating the sequence and quantification of impacts. Competition for water in these storage systems escalates during drought, and conflicts between water users increase significantly.

Finally, socioeconomic drought associates the supply and demand of some economic good or service with elements of meteorological, hydrological, and agricultural drought. Socioeconomic drought is associated directly with the supply of some commodity or economic good (e.g. water, hay, hydroelectric power) that is the result of precipitation shortages. Increases in population can alter substantially the demand for these economic goods over time. This concept of drought supports the strong symbiosis that exists between drought and its impacts and human activities. Thus, the incidence of drought could increase because of a change in the frequency of meteorological drought, a change in societal vulnerability to water shortages, or both.

Drought characteristics and severity

Droughts differ from one another in three essential characteristics: intensity, duration, and spatial coverage. Intensity refers to the degree of the precipitation shortfall and/or the severity of impacts associated with the shortfall. It is generally measured by the departure of some climatic index from normal and is closely linked to duration in the determination of impact. Another distinguishing feature of drought is its duration. Droughts usually require a minimum of 2–3 months to become established, but then can continue for months or years. The magnitude of drought impacts is closely related to the timing of the onset of the precipitation shortage, its intensity, and the duration of the event.

Droughts also differ in terms of their spatial characteristics. The areas affected by severe drought evolve gradually, and regions of maximum intensity shift from season to season. In larger countries, such as Brazil, China, India, the United States, or Australia, drought would rarely, if ever, affect the entire country. During the severe drought of the 1930s in the United States, for example, the area affected by severe and extreme drought never exceeded 65% of the country. However, because of its size and diverse climatic regimes, drought occurs somewhere in the country each year. From a planning perspective the spatial characteristics of drought have serious implications. Nations should determine the probability that drought may simultaneously affect all or several major crop-producing regions within their borders, and develop contingencies if such an event were to occur. Likewise, it is important for governments to know the chances of a regional drought simultaneously affecting agricultural productivity in their country as well as adjacent or nearby nations on whom they are dependent for food supplies.

The impacts of drought

The impacts of drought are diverse and often ripple through the economy. Thus, impacts are often referred to as direct or indirect. Because of the number of affected groups and sectors associated with drought, its spatial extent, and the difficulties connected with quantifying environmental damages and personal hardships, the precise determination of the financial costs of drought is an arduous task. It has been estimated that the average annual impacts of drought in the United States are $6–8 billion, but drought years often occur in clusters.

The impacts of drought can be classified into three principal areas: economic, environmental, and social. Economic impacts range from direct losses in the broad agricultural and agriculturally related sectors, including forestry and fishing, to losses in recreation, transportation, banking, and energy sectors. Environmental losses are the result of damages to plant and animal species, wildlife habitat, and air and water quality; forest and range fires; degradation of landscape quality; and soil erosion. Although these losses are difficult to quantify, growing public awareness and concern for environmental quality has forced public officials to focus greater attention on these effects. Social impacts mainly involve public safety, health, conflicts between water users, and inequities in the distribution of impacts and disaster relief programs. As with all natural hazards, the economic impacts of drought are highly variable within and between economic sectors and geographic regions, producing a complex assortment of winners and losers with the occurrence of each disaster.

Drought preparedness

Drought planning is defined as actions taken by individual citizens, industry, government, and others in advance of drought for the purpose of mitigating some of the impacts and conflicts associated with its occurrence. Because drought is a normal part of climate variability for virtually all regions, it is important to develop plans to deal with these extended periods of water shortage in a timely, systematic manner as they evolve. This planning process needs to occur at various levels of government and be integrated between levels of government.

The purpose of a drought policy and plan is to reduce the impacts of drought by identifying the principal sectors, groups, or regions most at risk and developing mitigation actions and programs that can reduce these risks in advance of future drought events. Generally, drought plans have three basic components: monitoring, early warning, and prediction; risk and impact assessment; and mitigation and response. Plans will also improve coordination within agencies of government and between levels of government. Before developing a preparedness plan, government officials should first define, in consultation with principal stakeholder groups, the goals of the plan.

The awareness of the need for drought planning has increased dramatically in both developed and developing countries. For example, in the United States, the number of states with drought plans has increased from three in 1982 to 34 in 2002. This trend demonstrates an increased concern about the potential impacts of extended water shortages and the complexity of those impacts. Drought plans are at the foundation of improved drought management, but only if they emphasize risk assessment and mitigation programs and actions.

Summary

Drought is an insidious natural hazard that is a normal part of the climate for virtually all regions. It should not be viewed as merely a physical phenomenon. Rather, drought is the result of an interplay between a natural event and the demand placed on water supply by human-use systems. Drought should be considered relative to some long-term average condition of balance between precipitation and evapotranspiration.

Many definitions of drought exist; it is unrealistic to expect a universal definition to be derived. The three characteristics that differentiate one drought from another are intensity, duration, and spatial extent. The impacts of drought are diverse and generally classified as economic, social, and environmental. Impacts ripple through the economy and may linger for years after the termination of the drought episode.

It appears that societal vulnerability to drought is escalating in both developing and developing countries, and at a significant rate. It is imperative that increased emphasis be placed on mitigation, preparedness, and prediction and early warning if society is to reduce the economic and environmental damages associated with drought and its personal hardships. This will require improved coordination within and between levels of government and the active participation of stakeholders.

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Cross-references

Agroclimatology
Arid Climates
Deserts
Climate Hazards
Desertification
Palmer Index/Palmer Drought Severity Index

DYNAMIC CLIMATOLOGY

Dynamic climatology, now frequently termed "climate dynamics", is an attempt to study and explain atmospheric circulation over a large part of the Earth in terms of the available sources and transformations of energy (Court, 1957). Hare (1957) notes that dynamic climatology is the prime approach for explanation of world climates as integrations of atmospheric circulation and disturbances. It also attempts to derive circulation types at the regional scale.

Agreement on the scope of dynamic climatology is not universal, and differences among dynamic, complex, and synoptic climatology are not always well defined. For example, Bergeron (1930) and others considered what is now synoptic climatology to be dynamic climatology. Interest in weather patterns among synoptic climatologists has also obscured contrasts with complex climatology. A history of the origin and content of dynamic climatology has been given by Rayner et al. (1991) while a modern survey of the field is available in a text by Barry and Carlton (2001).

Principles

The dynamic climatological approach is based on motion characteristics and the thermodynamic processes that produce them. Dynamic meteorologists have as their principal interest the development and interpretation of relationships that describe these latter items; their usage separates the climatologist from the meteorologist, although the boundary between the disciplines is a tenuous one. An excellent introduction to dynamics and thermodynamics as they apply to the atmosphere is contained in Hess (1959) and Atkinson (1981).

Moving air is the result of forces brought about by thermodynamic processes that originate primarily at the Earth–air interface. The driving force for all processes is the radiant energy supplied to the Earth–atmosphere system by the sun.

A small fraction of available solar energy is absorbed directly by atmospheric constituents. About three times as much energy reaches the surface of the Earth and is absorbed in differing amounts, depending on the geometry and physical properties of the surface. Various unevenly distributed energy sources and sinks are thus created. Energy is defined as the capacity to do work, to move an object (mass) through a distance by application of a force. Disposition of thermal energy in this case alters temperature, density, and pressure values, thereby yielding unbalanced vertical and horizontal forces that cause air to move. Heat, moisture, and momentum transfers result from such motions at various scales. Ultimately, the Earth–atmosphere system returns thermal energy to space through radiation in an amount equivalent to the solar energy originally received, thus balancing long-term gains and maintaining the atmospheric heat engine in a steady state.

The fundamental equations (often called the Primitive Equations) that describe processes and motion in the atmosphere are the Ideal Gas Law, the First Law of Thermodynamics, the Equation of Motion, the Equation of Moisture Conservation, and the Equation of Continuity (Table D4). They are used to describe the interactions and characteristics of the basic building blocks comprising the Earth–atmosphere system. Manipulations of the basic equations allow us to decipher relationships among thickness between layers in the atmosphere, temperature, the wind field, and to develop stability–change equations, pressure–tendency equations, and the vorticity equation, among others. Some concepts that follow from these relationships include geopotential and geopotential height, isobaric and constant level representations, streamlines and trajectories, circulation, and divergence.

Imperfect characterization

If the entire atmosphere could be confined to a laboratory setting, application of the equations in Table D4 would be a straightforward problem. Application to the real, unconfined atmosphere presents several difficulties. For example, data on the state of the atmosphere are not available at every point at all possible moments. This means that climatologists must work with average, or smoothed, data among sampled points. Unfortunately, such smoothing often eliminates small-scale density or temperature patterns that may have a significant but unknown effect at some location and time. Ramage (1978) points out that it is small-scale factors embedded within the atmosphere that prevent numerical weather forecasting efforts from being more accurate.

Lack of continuous, pervasive sampling also requires that boundaries be fixed on the edges of an area of interest; the west coast of the United States serves as one such large boundary because data on conditions over the Pacific Ocean are not widely available. Changes at the boundary become difficult to determine and ultimately filter through all equations used to characterize the atmosphere.

Turbulent eddies (small-scale air currents produced by frictional interaction by juxtaposed, unlike airmasses) also contribute substantially to the status of the atmosphere at any time. Again, unfortunately, the ability to describe energy transfers by

Table D4 Fundamental variables and equations

Variable	Equation
Pressure	Ideal Gas Law
Temperature	First Law of Thermodynamics
Density	Equation of Continuity
Moisture	Equation of Conservation of Moisture
Velocity	Equation of Motion

Source: After Panofsky (1956).

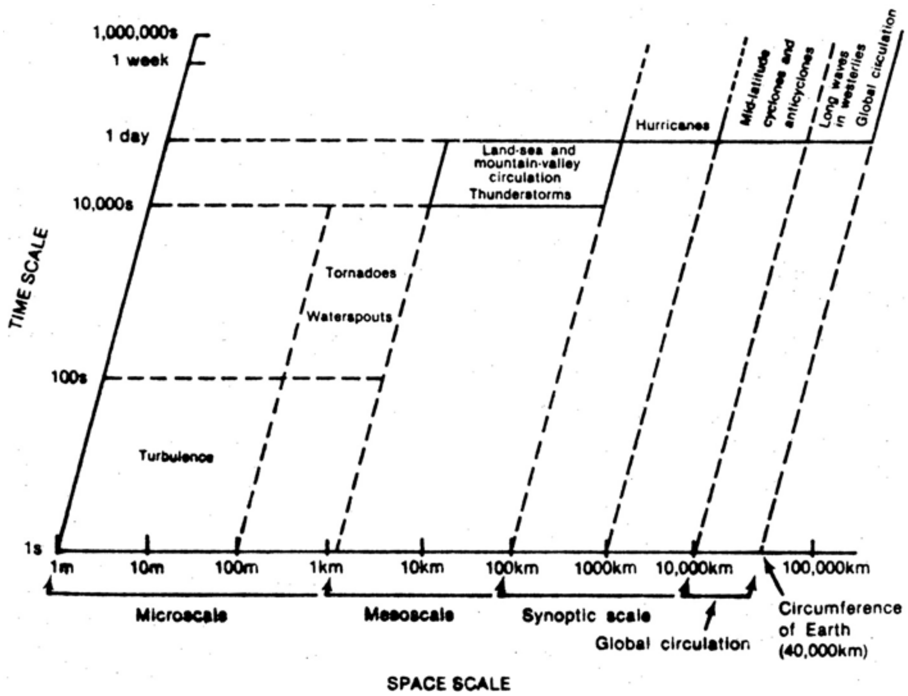

Figure D15 Time and space scales of atmospheric motion (after Anthes et al., 1981).

eddy conduction, diffusion and friction within the friction layer (the lowest 1500 m of the atmosphere) is limited; such transfers are neglected.

Finally, the basic equations used to describe the workings of the atmosphere are nonlinear. This means that, even at large scales, irregular fluctuations above and below mean values of variables do not cancel. Equations can be made to perform as though they were linear by using an artifice that considers all turbulent contributions as perturbations on the mean pattern. Given the contribution of turbulence to the mean state of the atmosphere, this introduces errors, is unsatisfactory, but is all that can be done at present without the use of numerical methods.

Description of motion

Although forces producing motion are interwoven in the atmospheric fabric, some equation terms and variables can be excluded at certain scales, because their contribution to an event or process is minimal (Figure D15). For example, at the level of the global circulation, vertical motion can be neglected, but not heat transfer, because at the global scale motion is overwhelmingly horizontal. On the other hand, certain microscale processes allow neglect of all thermodynamic equations and the variables temperature, moisture, and density if the atmosphere is considered incompressible. Thus, complexity is decreased without decreasing understanding of important processes and the results.

The Equation of Motion listed in Table D4 describes a vector and thus has three parts, each expressing Newton's Second Law of Motion (force = mass × acceleration) for three directions in a Cartesian system. Manipulations of this general equation yield the collective forces that must be specifically

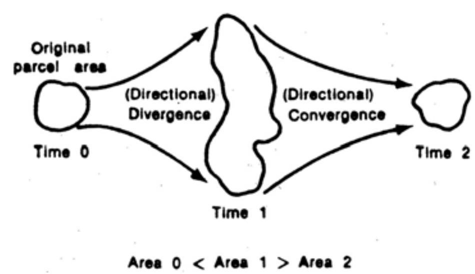

Figure D16 Horizontal divergence.

expressed; namely, gravity, pressure gradient, Coriolis force, and friction. Stated as a vector in words:

> Changes in velocity per unit time = Coriolis force + gravitational force − pressure gradient force + effect of friction.

Motion that takes place on a plane (two equations describe motion on a plane) above the friction layer between straight, parallel isobars (i.e. accelerations are not produced by the pressure field), is called the geostrophic wind, and is expressed as a balance between the pressure gradient and Coriolis forces. Consideration of curved isobars and the effect of friction yields other types of flow regimes, such as gradient (observed around low- and high-pressure systems), cyclostrophic (typical of tornadic circulation), and cross-isobaric motion due to the effect of friction on the velocity component of the geostrophic wind. Subtraction of geostrophic winds at two levels yields the thermal wind, which provides ties among thickness between layers, virtual temperature, and warm or cold air advection.

The third equation of motion applies to movement along a vertical axis. The Coriolis and frictional forces are neglected because their vertical components are small. Vertical motion then represents an interplay between an upward-directed pressure gradient force and gravity as a restoring force; this relationship is called the Hydrostatic Equation.

Manipulations of the three motion equations yield other concepts that are used in the dynamic climatological approach. For example, divergence and its opposite convergence occur when flow leads to increasing or decreasing area changes through time, as in Figure D16. Mass is neither created nor destroyed in the Earth–atmosphere system, and this principle (the First Law of Thermodynamics) stated in the form of the Equation of Continuity, ties changes in the horizontal with vertical motion (Figure D17). As the atmosphere contracts horizontally (converges), it expands vertically (stretches), and vice-versa. If we consider the troposphere as the region where these compensating mechanisms operate, then a general pattern like Figure D18 results. These patterns can also be related to vertical motion and typical convergence–divergence patterns in an eastward-moving upper-air wave system (Figure D19).

Finally, vorticity (which can be derived from the two horizontal equations of motion) area changes and vertical motion

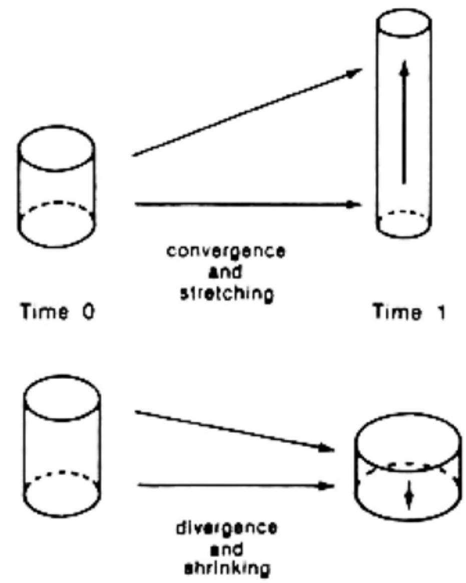

Figure D17 Convergence and stretching (upward vertical motion); divergence and shrinking (downward vertical motion).

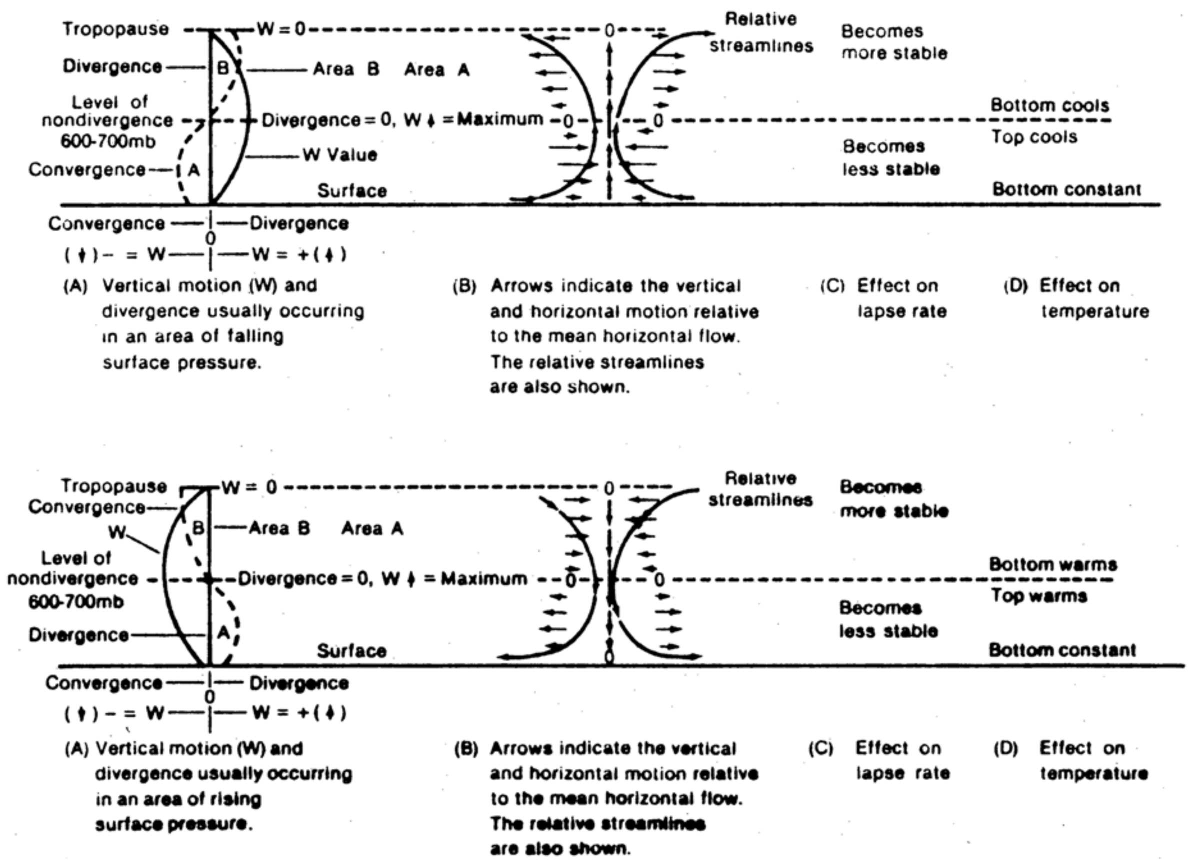

Figure D18 Convergence, divergence, and vertical motion in a typical atmospheric cross-section in the midlatitudes.

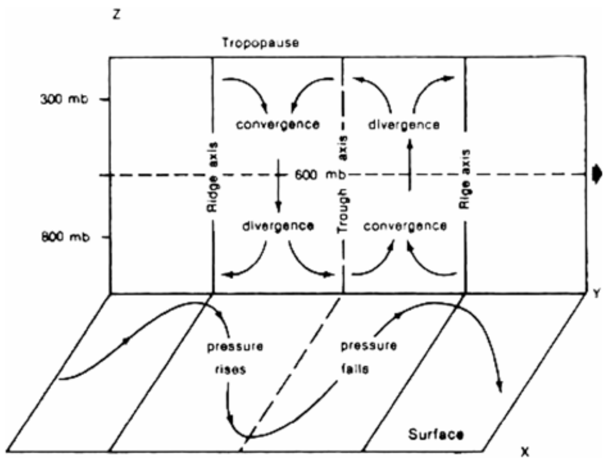

Figure D19 Organized patterns of convergence and divergence in an eastward-moving system in the midlatitudes.

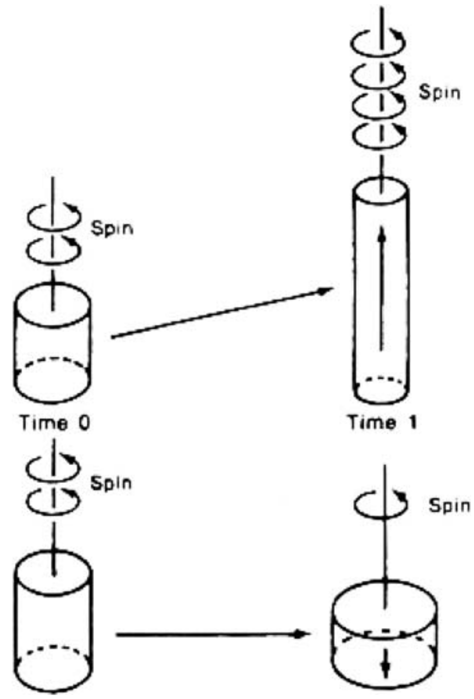

Figure D20 Relationship among vorticity, vertical motion, and area.

are related through the vorticity equation. Vorticity is defined as circulation (velocity along a closed path times the length of path) per unit area; since circulation for most processes is relatively constant through time, absolute vorticity (composed of relative plus Earth vorticity) times area is a constant. Again, equation of continuity is used to relate area changes to depth changes; i.e. decreases in area are related to convergence, upward motion, and positive vorticity (counterclockwise spin). Positive vorticity is normally associated with weather system development. Negative vorticity (clockwise spin) is associated with divergence, downward vertical motion, and lack of significant system development.

An example of the interplay among area, depth, and vorticity changes is shown on Figure D20. Figure D21 shows these latter items as they change when topographic changes are encountered. Lower-level air moving perpendicular to a topographic barrier is forced to ascend as it approaches. Decreases in absolute vorticity below the value that should exist at the given latitude occur as the cylinder reaches the mountain crest, causing an increase in divergence, subsidence, and ultimately anticyclonic deflection of the air parcel. As the column leaves the crest, the lower levels are free to expand, thereby increasing upward vertical motion and positive spin. The topographically forced condition depicted in the figure often is the situation prevailing to the lee of the Rocky Mountains, and may lead to development of large cyclonic storm systems.

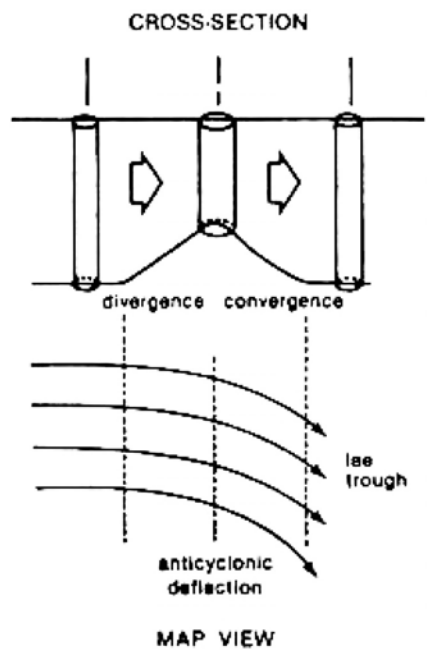

Figure D21 Patterns of convergence and divergence in an air current crossing a topographic barrier.

Thermodynamic processes

The use of thermodynamic principles shows how changes in heat content of the atmosphere, which behaves as a fluid under most circumstances, affect its dynamic characteristics. Volume and pressure changes within the atmosphere are produced by heat addition to, or subtraction from, an air parcel or by work done on or by the parcel within its surroundings. Thermodynamic laws describe what occurs among pressure, volume, and heat content as changes take place.

For example, the First Law of Thermodynamics states that heat added to a parcel can be used to increase its internal energy or to do work on its surrounding environment. From the First Law we can derive the adiabatic relationship, which states that all temperature changes within a parcel are due to expansion or compression if no external heat is added or taken away. External heat may come from radiation, eddy heat conduction, evaporation, or condensation. The adiabatic relationship allows stability to be determined and tells us what will happen to parcel air temperatures as parcels move about in the atmosphere.

The state of the atmosphere at any moment can be described by application of the Ideal Gas Law, which relates pressure, density, virtual temperature, and a gas constant for air. The Moisture Equation allows determination of changes in water vapor content of air parcels through time. The equation relates changes in specific humidity (grams of water vapor per unit mass of air including moisture) to occurrence of condensation, evaporation, molecular diffusion and eddy diffusion of vapor between unlike air masses.

Glen A. Marotz

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Cross-references

Atmospheric Circulation, Global
Climatology
Coriolis Effect
Jet Streams
Rossby Wave/Rossby Number
Synoptic Climatology
Vorticity
Winds and Wind Systems