World Climatic Systems

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Preface

The importance of climatology to various human activities has been growing in recent years. This is seen particularly in the fields of agriculture and energy use. Over the last decade climatic variations, including widespread drought in tropical countries, have caused major crop failures. Tropical deserts appear to be extending and this is sometimes blamed on incorrect agricultural techniques. Man has also upset the global carbon cycle by burning fossil fuels and by deforestation and changing land use. The net result of these activities has been to increase the CO_2 content of the atmosphere and the oceans, and to cause changes in both global temperature distributions and the global hydrological cycle over the next 50 years. The various climatic systems involved in these important areas of human activity are described in *World Climatic Systems*.

World Climatic Systems provides second and third year University and Polytechnic students in geography, environmental science, and related subjects such as agriculture, with a broad picture of the major climatic processes. It also forms a background text for postgraduate students in the climatological sciences. It is complementary to *Causes of Climate*, and assumes some basic knowledge of mathematics and physics, which should not be beyond physical geography students.

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University of Leeds
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1 The General Atmospheric Circulation

1 The climatic system

A system may be defined as a structural set of objects and/or attributes, where these objects and attributes consist of components or variables that exhibit discernible relationships with one another and operate together as a complex whole, according to some observed pattern. The concept of the system is very useful in providing a means of understanding complex phenomena, provided that it is clearly understood that systems try to describe what happens in nature, and that nature cannot necessarily be forced into the mould of some particular preconceived system. Systems can be classified in terms of their function and also in terms of their internal complexity.

1.1 Isolated, closed and open systems

A common functional division is into isolated, closed and open systems.

(a) *Isolated systems* have boundaries which are closed to the import and export of both mass and energy. Such systems are rare in the real world, though they may occur in the laboratory, i.e. a mass of gas within a completely sealed and insulated container.

(b) *A closed system* is one in which there is no exchange of matter between the system and its environment though there is, in general, an exchange of energy. The planet earth together with its atmosphere may, very nearly, be considered a closed system.

(c) *An open system* is one in which there is an exchange of both matter and energy between the system and its environment. There are numerous examples of open systems in nature, i.e. precipitating clouds, river catchments, plants, etc.

Isolated systems

Gas within a completely sealed and insulated container provides a good example of an isolated system. Whatever the original temperature gradients within the gas, temperatures will eventually become uniform, and while the system remains isolated nothing can check or hinder this inevitable levelling down of differences. Stated more generally, in an isolated system there is a tendency for the levelling down of existing differentiation within the system, and towards the progressive destruction of the existing order. In such a system there is always a decrease in the amount of free energy available for causing changes and doing work, and eventually the free energy will become zero.

Open systems

Open systems need an energy supply for their maintenance and preservation, and are in effect maintained by the constant supply and removal of material and energy. Closed systems may be considered as a special case of open systems, there being no exchange of matter with the environment. It has already been noted that most of the systems observed within the natural environment belong to the open group. In particular, the open system has one important property which is not found in the isolated system, that is, it may attain a condition known as steady-state equilibrium. This is the condition of an open system wherein its properties are invariant when considered with reference to a given time-scale, but within which its instantaneous condition may oscillate due to the presence of interacting variables. Stated rather more simply, the general features of the system appear to remain constant over a long period of time, though there may be minor changes in details. Meteorological storms, such as hurricanes or thunderstorms, are good examples of open systems in a steady state, in that their general features remain relatively constant over periods of time ranging from several days in the case of the hurricane to several hours for a thunderstorm.

Open systems in the natural environment can be divided into three general categories, which may be termed decaying, cyclic and haphazardly fluctuating. Some systems always belong to one broad category while others change from one to another over relatively short periods of time.

Decaying systems consume their own substance, which may be energy or matter, or both. A good example is the decay of river-flow in dry weather, when the flow decreases each day but the rate at which the flow decreases also decreases with time and is proportional to the available water stored in the rocks. The rocks in the river catchmnt act as a store which supplies water to the river. In this case the river-flow approximates to a negative-exponential decay curve, and the amount of water stored in the rocks decreases to one-half of its original value in a given constant time interval.

The input of short-wave radiation follows diurnal and annual cycles, and these are imposed on many natural systems to form cyclic systems. Heat balances of land surfaces are largely controlled by the input of solar energy, and therefore show both diurnal and annual cycles. Air temperatures reflect the state of the heat balance of the surface and therefore also show marked diurnal and annual cycles. The variations in many cyclic systems when observed over a period of time appear to approximate to a mathematical curve known as a sine curve, which may be obtained by plotting the sine of an angle against the angle itself.

Haphazardly fluctuating systems change in a random and irregular manner, fluctuations occurring at unpredictable times and by unpredictable amounts. Turbulence in fluids or the occurrence of earthquakes are good examples, since neither can be exactly predicted. On small space- and time-scales most systems exhibit some degree of unpredictability.

1.2 Cascading systems and the atmosphere

From a climatological viewpoint, the atmosphere, oceans and land surfaces may be considered as consisting of a series of open systems of the type known as cascading systems.

Cascading systems are composed of a chain of subsystems, having both magnitude and geographical location, which are dynamically linked by a cascade of mass or energy and in this way, the output of mass or energy from one subsystem becomes the input for the next subsystem. Typically, the subsystems consist of an input into a store, which may contain a regulator controlling the amount of mass or energy remaining in the store or forming the output. The regulator may be a physical property of the store itself or it may be completely external to the store. More complex subsystems may have several inputs and outputs and even several regulators which decide how the mass or energy is divided between the various outputs. Many of the processes taking place in the atmosphere can be interpreted in terms of cascading systems, an example being provided by the cycle of water. Water may be stored in the oceans, the atmosphere (as water vapour), the soil, the deep rocks, rivers, etc., and the transfer of water from one store to another is controlled by various physical regulators. The output from the atmospheric store in the form of rain constitutes the input into the soil, where in turn one of the outputs forms the input into the deep rock storage, and so on until the water arrives back into the ocean where evaporation forms the input into the atmospheric store.

Interception of rainfall by a forest is a good example of a subsystem. The amount of water that can be carried on a leaf surface is limited, and so there is a definite upper limit to the amount of water that can be stored in a tree canopy and thus to the store of the subsystem. The input into the subsystem is rainfall and the outputs are the evaporation of the intercepted water and the gradual drip of water out of the trees onto the soil surface. At the start of the rainfall the tree canopies will be dry and no water will reach the soil, except through holes in the canopy. After some time the canopies will become completely saturated with water, and when this occurs most of the succeeding rainfall will eventually drip onto the soil surface. So the regulators controlling the amount of water reaching the soil will be the physical geometry of the tree canopies and the percentage saturation of the canopies. There is also a loss of water by evaporation from intercepted water in the canopies. This loss is controlled by the prevailing meteorological conditions and thus by a regulator which is outside of the physical bounds of the subsystem.

The climatic system consists of those properties and processes that are responsible for climate. The properties of the climatic system may be broadly classified as: thermal properties, which include the temperature of the air, water, ice and land; kinetic properties, which include the wind and ocean currents, together with the associated vertical motions, and the motion of ice masses; aqueous properties; which include the air's moisture or humidity, the cloudiness and cloud water content, groundwater, lake levels, and the water content of snow and of land- and sea-ice; and static properties, which include the pressure and density of the atmosphere and ocean, the composition of the air, the oceanic salinity, and the geometric boundaries and physical constants of the system. These variables are interconnected by the various physical processes occurring within the system, such as precipitation and evaporation, radiation, and the transfer of energy by advection and turbulence.

1.3 Physical components

It is normal to divide the complete climatic system into five physical components – the atmosphere, hydrosphere, cryosphere, lithosphere and biosphere. These components have quite different physical characteristics, and are linked to each other and to conditions external to the system by a variety of physical processes. The atmosphere is the central component of the climatic system, and displays a spectrum of conditions varying from microclimates to the climate of the entire planet. Because of the ease with which the atmosphere can be heated and set in motion, it may generally be expected to respond to an imposed change more rapidly than the other components of the climatic system. A close second to the atmosphere in terms of its overall importance in the climatic system is the hydrosphere. The extent and bulk of the world's oceans and the prevalence of surface water on the land ensures a potentially plentiful supply of water for the global hydrological cycle of evaporation, condensation, precipitation and run-off. The cryosphere, like the hydrosphere, consists of a portion closely associated with the sea (sea-ice) and portions associated with the land (snow, glaciers and ice sheets). The importance of the cryosphere to the climatic system lies in the high albedo and low thermal conductivity of snow and ice. The surface lithosphere, in contrast to the atmosphere, hydrosphere and cryosphere, is a relatively passive component of the climatic system. An exception to this is the amount of soil moisture which is closely related to the local surface and ground hydrology. Soil moisture exerts a marked influence on the local surface balance of moisture and heat, through its influence on the surface evaporation rate and on the soil's albedo and thermal conductivity. The remaining component of the climatic system, the surface biomass, interacts with the other components on time-scales which are characteristic of the life cycles of the earth's vegetative cover. The trees, ~~plants~~ and ground-cover modify the surface radiation balance and surface heat flux, and play a major role in the seasonal variations of local surface hydrology.

1.4 Further development

World Climatic Systems considers the components of the global climatic system in detail. There are chapters on the general atmospheric circulation, oceanic subsystems, glacial subsystems, and also two chapters looking at aspects of atmospheric interactions with the biosphere. The hydrosphere is a central theme throughout much of the book, while interactions with the lithosphere in the form of soil moisture and albedo are discussed in a number of places. The major components of the climatic system are considered in Part I of the book. The importance of climatology to various human activities has been growing in recent years. This is seen particularly in the fields of agriculture and energy use. Man has upset the global carbon cycle by burning fossil fuels and by deforestation and changing land use. The net result of these activities has been to increase the CO_2 content of the atmosphere and the oceans, and to cause future changes in both global temperature distributions and the global hydrological cycle, including the incidence of drought. Some of these applied aspects of the climatic system are considered in Part II on Impacts of the Climatic System.

2 Driving forces

The global atmosphere circulation consists of the observed wind systems with their annual and seasonal variations, and is the principal factor determining the distribution of climatic zones. The two major causes of the global wind circulation are inequalities in radiation distribution over the earth's surface and the earth's rotation. The global radiation distribution drives the global circulation while the earth's rotation determines its shape. Basically the mean surface circulation consists of easterly winds with equatorial components in the tropics and westerly winds with poleward components in middle latitudes, the corresponding meridional flows aloft being reversed. Weak surface easterlies are found in the polar regions and extensive areas of calms in the equatorial and subtropical regions. Strong upper westerly winds are found poleward of about 25°N and S.

2.1 Radiation distribution

The planet earth receives heat from the sun in the form of short-wave radiation, but it also radiates an equal amount of heat to space in the form of long-wave radiation. This balance of heat gained equalling heat lost only applies to the planet as a whole over several annual periods; it does not apply to any specific area for a short period of time. The equatorial region absorbs more heat than it loses, while the polar regions radiate more heat than they receive. The distribution of radiation over the earth's surface is reviewed in Lockwood (1979). Nevertheless, the equatorial belt does not become warmer during the year, nor do the poles become colder, because heat flows from the warm to the cold regions, thus maintaining the observed temperatures. An exchange of heat is brought about by the motion of the atmosphere and upper layers of the oceans, thus forming the general circulation of the atmosphere and oceans.

Global radiation

Global radiation is the sum of all short-wave radiation received, both directly from the sun and indirectly from the sky, on a horizontal surface. Generalized isolines of average annual global radiation are shown in Figure 1.1, which conveys a very general picture of the distribution of global radiation. The actual distribution of global radiation reflects closely astronomical factors and the distribution of cloud. Thus the areas receiving most global radiation are found in the subtropics where there are unusually clear skies because of the prevailing anticyclonic conditions.

Albedo

Radiation reflected directly back to space from the earth constitutes a loss of available energy to the earth–atmosphere system. The distribution of albedo values over the earth's surface must therefore be considered together with the global radiation. The annual albedo of the earth–atmosphere system is shown in Figure 1.2. The albedo map clearly reveals the land–sea distribution and the general atmospheric circulation as it is represented by the mean cloud patterns over both hemispheres. The high-reaching convective clouds associated with the intertropical convergence zones and partly with the Asian monsoon appear as a belt of relatively high albedos of more than 25–30 per cent. Similarly, low persistent stratus clouds along the western coastal areas of North and South America and Africa appear with albedos between 25 and 35 per cent. The albedo of both polar regions is considerably higher than 50 per cent because of the associated permanent snow and ice-fields. Regions of major gain of radiative energy are the oceanic areas in the subtropics of both hemispheres. The planetary albedo shown in Figure 1.2 is made up of three main components. These are the light reflected from the actual land and sea surfaces of the earth, the light reflected by clouds, and the light scattered upwards by the atmosphere. Estimates of the albedo of the ground and also locations of persistent cloud fields and of ice and snow can be made when travelling or otherwise changing cloud-fields are removed by displaying only the lowest observed satellite albedo value in each area. This approach is based on the simple assumption that the albedo of the earth–atmosphere system is higher over each area in the presence of clouds than for a cloud-free atmosphere. A map produced by Raschke *et al.* (1973) in this manner shows the much lower albedos observed over the oceans as compared with those over the continents. Similarly over Africa the high albedos of the desert surfaces are clearly to be seen, with a relatively sharp boundary where the southern Sahara grades into regions with rather more vegetation. Minimum albedos greater than 40 per cent belong to ice-fields at their smallest extent during July over the Arctic and during January over the Antarctic, respectively.

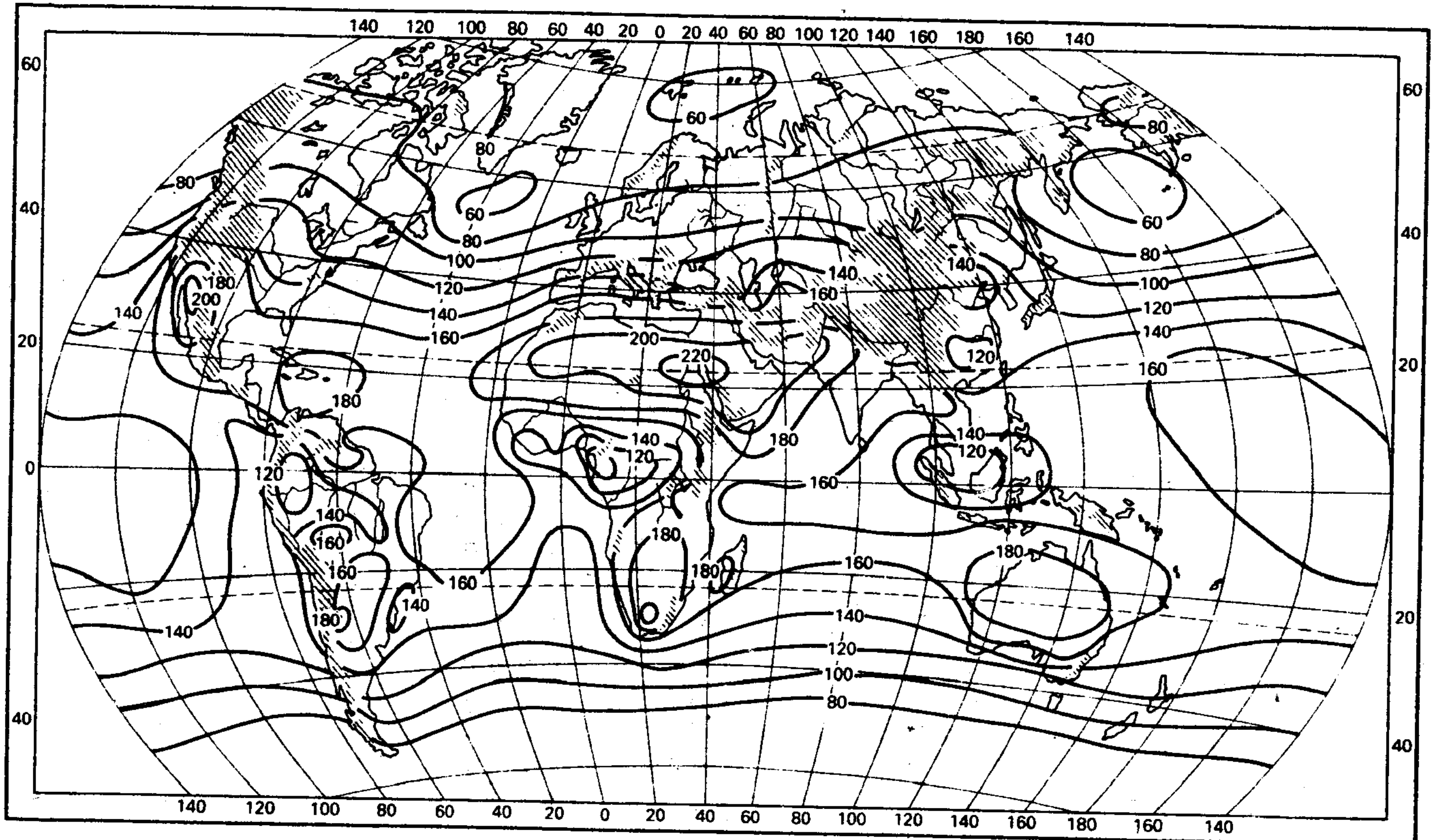

Figure 1.1 Average annual global radiation (Kcal cm^{-2} yr^{-1}) (1 cal cm^{-2} min^{-1} = 698 W m^{-2}) (after Budyko, 1974).

Nimbus 3 1969-1970

Albedo (per cent)

Figure 1.2 Annual albedo of the earth-atmosphere system (after Raschke *et al.*, 1973).

Outgoing long-wave radiation

The outgoing long-wave radiation distribution reflects the temperatures of the emitting surfaces. Thus high clouds are cold and have a low emission, while low-level surfaces are warm and have a high rate of emission. Over Africa, low rates of emission are observed from the high convective clouds of the intertropical convergence zone while over the Sahara high rates are observed since the atmosphere is clear and the warm sands of the desert surface are visible.

Outgoing radiation from the whole globe corresponds to an effective temperature of 255 K, and the planetary albedo is found to be about 30 per cent.

Radiation balance

Figure 1.3 shows the geographical distribution of annual net radiation at the earth's surface only, for the atmosphere is excluded. This figure reveals that the annual means of the net radiation balance over the greater part of the earth's surface are positive, and thus signifies that the absorbed short-wave radiation is greater than the long-wave outgoing radiation. This pattern is the result of the greater transparency of the atmosphere for short-wave radiation in comparison with long-wave radiation, and the excess of energy at the earth's surface is transferred to the atmosphere by turbulent heat exchange and by evaporation.

A satellite estimate of the annual radiation balance of the earth–atmosphere system is shown in Figure 1.4. Positive values, mostly found between 40°N and 40°S, imply a heat gain by the surface–atmosphere system, while negative values elsewhere imply a general heat loss to space. The net radiation integrated over the whole globe must come to zero, because there is, over an annual period, almost an exact balance between solar energy absorbed and infrared radiation emitted to space. Significant changes in the earth's radiation budget occur within latitudinal zones, especially in the tropics. Thus the areas of the major gains of radiative energy are the oceans in the subtropics of both hemispheres, while the African and Arabian deserts at the same latitude actually have a radiative deficit.

Seasonal changes of radiation balance are dominated by seasonal variations in solar declination. The radiative balance of the surface–atmosphere system is positive during the whole year only in the narrow equatorial zone between the latitudes 10°N to 10°S, for elsewhere the sign of the radiation balance changes twice a year. For about 3 summer months in a year the radiation balance of the whole of each hemisphere is positive, but in late summer, zones of negative balance arise near the poles and then gradually spread towards the equator, reaching latitude 30 after 5 months; a similar process of retreat begins in the spring.

If the earth's surface were homogeneous and the planet were not rotating, the imposition of a latitudinal heating gradient would result in a single circulation cell in each hemisphere with an upward limb at the equator and downward limbs at the poles. These cells are energetically direct cells because they are the result of a transformation of potential to kinetic energy. They are often referred to as Hadley cells in tribute to the eighteenth-century scientist who first deduced their existence.

2.2 The earth's rotation

When the earth rotates, the situation is altered in a number of ways, since the rotation generates east–west motions in the atmosphere. To an observer on the rotating earth it appears that a force is acting on moving air particles which causes them to be deflected from their original path, and this apparent force per unit mass is termed the 'Coriolis force'. The Coriolis force turns the wind to the right relative to