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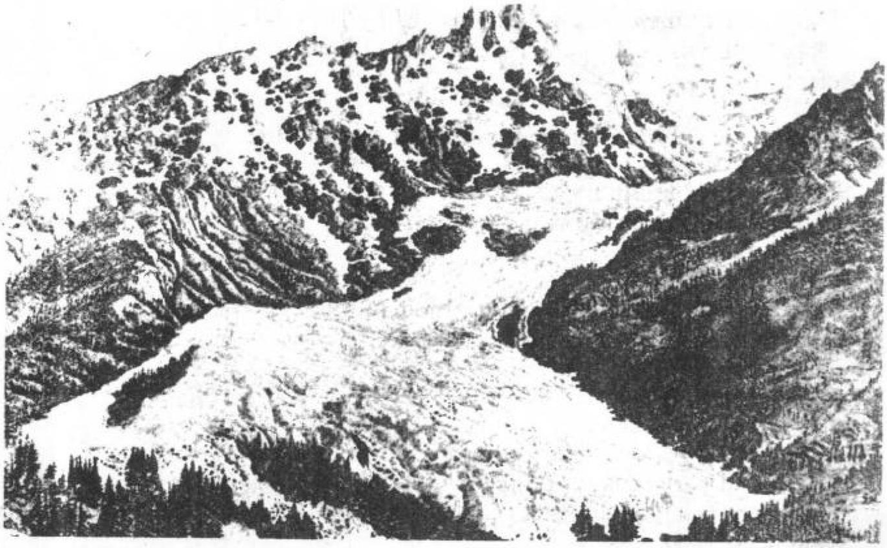

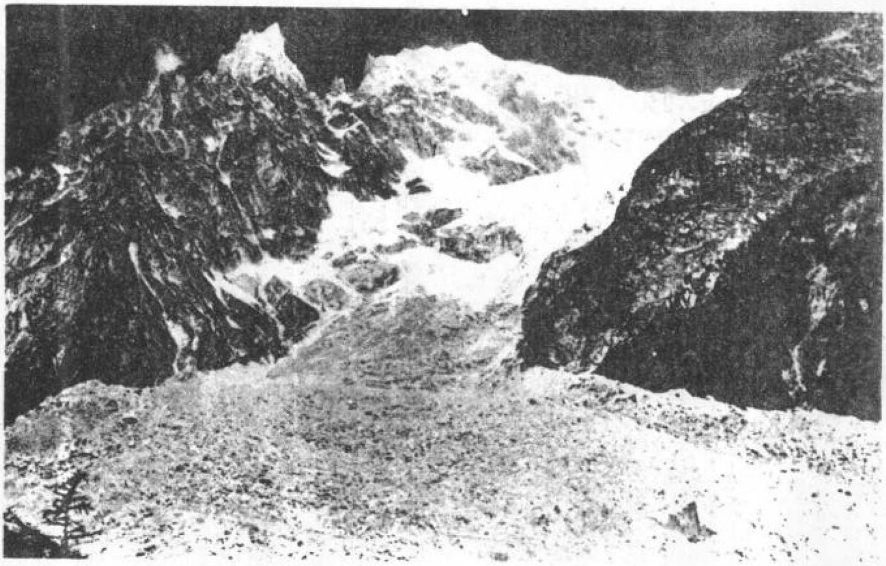

The warming trend experienced in the northern hemisphere during the early part of this century has led to glacier retreat in most areas. The illustration shows the Alpine Glacier de la Brenva, in 1767 and 1966. The sketch (above) by Jalabert is remarkably accurate, showing an advanced glacier position in 1767. The photograph (below) from 1966 shows the massive Little Ice Age moraine. *Reproduced by permission of E. Le Roy Ladurie.*

Preface

Causes of Climate has been written for first and second year university, polytechnic and college students in geography and environmental sciences. It is intended to provide arts and social science students with an introduction to modern climatology, and science students with a basis for further advanced study. There is a growing interest in climatic change, and the search for causes of climatic variations on all time-scales now forms a major part of climatology. This book therefore considers the various explanations of climatic change in detail, though it is not meant to be a history of climate. Since explanations of long- and medium-term climatic change depend on modifications or variations in the solar energy reaching the earth's surface, considerable amount of space is given to radiation theory. To many students this may seem an unusual and unnecessary excursion into physics, but it is necessary if the physical bases of modern theories of climatic change are to be understood. As most geography students are required to study elementary mathematics and statistics, simple equations are used in the book where necessary.

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John G. Lockwood

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Introduction: The Climatic System

The term climate usually brings to mind an average regime of weather. However, the mechanisms that create the earth's climate and its variations are part of an enormously complex physical system, which includes not only the relatively well known behaviour of the atmosphere, but also the less well known behaviour of the world's ocean and ice masses, together with the variations occurring at the earth's surface. In addition to physical factors there are complex chemical and biological processes affecting the climate, which are also of importance for the climate's impact on living things and thus on man.

The application of both systems theory and mathematics to climatology has changed the subject completely in recent years. The use of systems theory and mathematical models enables the immensely complex real world to be examined and thought about in an orderly, logical manner. Associated with the growth of this systems approach has been a change from the simple description of climatic statistics to a study of the various interactions and exchanges which shape the climatic environment. Classical climatology is concerned with listing averages and extremes of the various climatological elements, but has little to say about the causes of climate. In contrast, modern climatology is concerned with describing the actual causes of climate, and also the causes of any climatic variations. In climatology, the major exchanges consist of flows of energy and water, and much recent research is concerned with tracing the pathways of these particular flows. As mentioned earlier, much use is made of models and the concept of climatological systems, so before discussing basic climatology it is necessary to discuss systems in detail.

1 Systems

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.

1.1.1 *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.

1.1.2 *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 catchment 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.

Systems may also be classified according to their internal complexity, and one frequent type of open system which is found in nature is the cascading system. 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, 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 and the natural environment in general can be interpreted in terms of cascading systems, a good 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 than 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, but 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 regulator 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 the 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.

2 The climatic system

From a climatological viewpoint, the atmosphere, oceans and land surfaces may be considered as consisting of a series of cascading systems connected by flows of mass or energy. The hydrological cycle is a good example of such a cascading system, and is discussed in detail in Chapter 4 and illustrated in Figure 4.29. It describes the circulation of water from the oceans, through the atmosphere and back to the oceans, or to the land and thence to the oceans again by overland and subterranean routes. On a global scale it is possible to recognize four major water reservoirs which are the world oceans, polar ice, terrestrial waters, and atmospheric waters. Water in the oceans evaporates under the influence of solar radiation and the resulting clouds of water vapour are transported by the atmospheric circulation to the land areas, where precipitation may occur and the resulting liquid water flow back to the oceans under the influence of gravity. Thus there are two main energy inputs driving the hydrological cycle, and these are gravity and solar radiation. Gravity causes liquid water to run downhill, and under its influence all water would eventually accumulate in the oceans. Solar radiation by causing evaporation, lifts water as water vapour into the atmosphere against the force of gravity. Since this water vapour condenses over the land masses and runs back to the sea, solar radiation allows the hydrological cycle to continue to function. The hydrological cycle is thus driven by a continuous supply of energy from the sun and would soon cease without this particular energy input.

In the same manner that gravity causes water to accumulate in the oceans and leave the lands dry, so friction slows and eventually destroys all motions in the atmosphere and oceans. In the real atmosphere the energy of motion destroyed by frictional forces is replaced by fresh energy derived from solar radiation. So a simple cascade of energy can be recognized in the atmosphere and oceans, since solar radiation is converted into heat which in turn is converted into motion. Motion is destroyed by friction which turns it back into heat, which is lost to space as infrared radiation.

The climatic system consists of those properties and processes that are responsible for the climate and its variations and are illustrated in Figure 1.1. The US National Academy of Sciences (1975) suggests that the properties of the climatic system may be broadly classified as: thermal properties, which include the temperatures of the air, water, ice, and land; kinetic properties, which includes 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.

According to the US National Academy of Sciences the complete climatic system consists of five physical components—the atmosphere, hydrosphere, cryosphere, lithosphere and biosphere. Briefly, they may be described as follows:

Atmosphere This comprises the earth's gaseous envelope, and is the most variable part of the system. The atmosphere, by transferring heat vertically and horizontally, adjusts itself to an imposed temperature change in about a month's time. This is also approximately the time it will take for the atmosphere's kinetic energy to be dissipated by friction, if there were no processes acting to replenish this energy.

Hydrosphere This comprises the liquid water distributed over the surface of the earth, including the oceans, lakes, rivers and groundwater. Of these, the world's oceans are the most important for climatic variations. The ocean absorbs most of the solar radiation that reaches the earth's surface, and also represents an enormous reservoir of heat due to the relatively large mass and specific heat of the ocean's water.

Cryosphere This comprises the world's ice masses and snow deposits, which includes the continental ice sheets, mountain glaciers, sea ice, surface snow cover, and lake and river ice. Changes in snow cover are mainly seasonal in character, while glaciers and ice sheets respond much more slowly. Glaciers and ice sheets only show significant changes in volume and extent over periods ranging from hundreds to millions of years.

Lithosphere This consists of the land masses over the surface of the earth, and includes the mountain and ocean basins, together with the surface rock, sediments, and soil. These features change over the longest time scales of all, the components of the climatic system ranging up to the age of the earth itself.

Biosphere This includes the plant cover on land and in the ocean and the animals of the air, sea and land. Biological elements are sensitive to climate and, in turn, may influence climatic changes.

Primary among the processes responsible for climate is the rate at which heat is added to the climatic system, the ultimate source of which is of course the sun's radiation. The atmosphere and the oceans respond to this heating by developing winds and currents, which in turn serve to transport heat from regions where it is received in abundance to regions where there is a thermal deficit. A great deal of this heat is transported by the large-scale transient disturbances in the atmosphere and ocean. Because of the large thermal capacity of the system compared to the rate of heating, individual large-scale weather systems are, within their lifetimes of about one week, relatively little affected by heating. Beyond a few weeks, on the other hand, the heating becomes essential for re-supplying the energy of the atmospheric system. This is why so much attention is given to radiation and energy supply in this book which is basically about climate.

2.1 The nature of energy

Energy may formally be defined as the capacity for doing work, and it may exist in a variety of forms including heat, radiation, potential energy, kinetic energy, chemical energy, and electric and magnetic energies. It is a property of matter capable of being transferred from one place to another, of changing the environment and is itself susceptible to change from one form to another. An example of energy changing the environment is provided by solar radiation falling on a field during the early morning and increasing both the temperature of the air and of the plants. Another example is the energy of high winds or floods which may change the natural environment in a far more spectacular and destructive manner. If nuclear reactions are excluded, it can be stated that energy is neither created nor destroyed, and from this it follows that all forms of energy are exactly convertible to all other forms of energy, though not all transformations are equally likely. It is therefore possible for any particular system to produce an exact energy account, in which the energy gained exactly equals the energy loss plus any change in storage of energy in the system. Since a continuous transformation of energy from one form into another takes place in the atmosphere and on the earth's surface, it is necessary to consider in some detail the various forms which energy can assume.

2.1.1 *Heat*

Heat is a form of energy and it defines in a general way the aggregate internal energy of motion of the atoms and molecules of a body. It may be taken as being equivalent to the specific heat of a body multiplied by its absolute temperature in degrees Kelvin and by its mass, where the specific heat of a substance is the heat required to raise the temperature of a unit mass by one degree. It is important to distinguish between temperature and heat, for temperature is a measure of the mean kinetic energy (speed) per molecule of the molecules in an object, while heat is a measure of the total kinetic energy of all the molecules of that object. As the temperature increases so does the mean kinetic energy of the molecules, and conversely it is possible to imagine a state when the molecules are at complete rest, a point on the temperature scale known as absolute zero. This has been found to be at 273·15 Celsius degrees below the melting point of ice (0 °C), and the Kelvin temperature scale is measured from absolute zero in Celsius units making 0 °C equivalent to 273·15 K. The Kelvin temperature scale is used in basic physical equations which involve temperature and it has the practical advantage of avoiding negative values.

Temperature is the condition which determines the flow of heat from one substance to another, the direction being from high to low temperatures. So long as only one object is considered, its temperature changes represent proportional changes in heat content. The definition of heat content suggests that when a variety of masses and types of material are considered, the equivalence of heat and temperature disappears. Often a small hot object will contain considerably less heat than a large cool one, and even if both have the same mass and temperature their heat contents can differ because of differing specific heats.

The transfer of heat to or from a substance is effected by one or more of the processes of conduction, convection or radiation. The common effect of such a transfer is to alter either the temperature or the state of the substance or both. Thus, a heated body may acquire a higher temperature (sensible heat) or change to a higher state (liquid to gas, or solid to liquid) and therefore acquire latent or hidden heat. Conduction is the process of heat transfer through matter by molecular impact from regions of high temperature to regions of low temperature without the transfer of the matter itself. It is the process by which heat passes through solids but its effects in fluids (liquids and gases) are usually negligible in comparison with those of convection. In contrast, convection is a mode of heat transfer in a fluid, involving the movement of substantial volumes of the substance concerned. Conduction is the main method of heat transfer in the solid rocks and the soil, while the convection process frequently operates in the atmosphere and oceans.

2.1.2 *Radiation*

This is the transmission of energy by electromagnetic waves, which may be propagated through a substance or through a vacuum at the speed of light. Electromagnetic radiation is divided into various classes which differ only in wavelength; these are, in order of increasing wavelength: gamma radiation, X-rays, ultraviolet radiation, visible radiation, infrared radiation and radio waves. All objects which are not at the absolute zero of temperature give off radiant energy to the surrounding space, so the environment is full of radiation of various wavelengths, the most important of which are in the visible and infrared sections. Furthermore, since nearly all the available energy in the natural environment was originally gained as visible radiation from the sun, the study of radiation is obviously of great importance and is considered separately in greater detail in the next chapter.

For the sun, the wavelength of maximum emission is near 0·5 μm (10^{-6} m), which is in the visible portion of the electromagnetic spectrum, and almost 99 per cent of the sun's radiation is contained in the so called short wavelengths from 0·15 to 4·0 μm. Observations show that 9 per cent of this short-wave radiation is in the ultraviolet (less than 0·4 μm), 45 per cent in the visible (0·4 to 0·7 μm) and 46 per cent in the infrared (greater than 0·74 μm). The surface of the earth, when heated by the absorption of solar radiation, becomes a source of long-wave radiation. The average temperature of the earth's surface is about 285 K, and therefore most of the radiation is emitted in the infrared spectral range from 4 to 50 μm, with a peak near 10 μm. This radiation may be referred to as long-wave, infrared, terrestrial or thermal radiation. Net radiation is the difference between the total incoming and total outgoing radiation, and clearly it shows whether net heating or cooling is taking place.

2.1.3 *Potential energy*

This is the energy possessed by a body by virtue of its position. It is measured by the amount of work required to bring the body from a standard position, where its potential energy is zero, to its present position. Thus a body at some distance above the ground has more gravitational potential energy than a body at ground level, and if released the potential energy will be converted into kinetic energy as the object accelerates towards the earth. Rivers are good examples of the conversion of potential energy into kinetic energy. Water vapour in the atmosphere possesses some gravitational potential energy in respect of its altitude above sea-level, and this potential energy is converted into kinetic energy when it condenses into rain which then falls towards the ground. If the rain reaches sea-level, then all the gravitational potential energy of the rainwater will have been converted into kinetic energy, but in contrast, if it falls on an upland surface, some potential energy will still be available and this will appear as the energy of river-flow as the water moves towards the sea along stream channels.

2.1.4 *Kinetic energy*

This is the energy possessed by a body by virtue of its motion. It is a quantity of magnitude $\frac{1}{2} MV^2$, where M is the mass and V the velocity of the particle. Kinetic energy is continuously dissipated by the various resistances to motion, and is often converted into heat. The kinetic energy of rivers is dissipated by the resistance to water movement created by the uneven stream floor. Since this resistance is very large, rivers normally flow only very slowly, suggesting that kinetic energy is being destroyed almost as fast as it is created from the gravitational potential energy of the water. The atmosphere contains kinetic energy because of the winds, and this is dissipated mainly by friction at the ground surface. It is estimated that, in the absence of solar radiation which creates kinetic energy, dissipation of the atmosphere's kinetic energy by friction would be almost complete after six days. Kinetic energy is therefore, in the natural environment, one of the less