10

The Global Water Cycle

Introduction

The annual circulation of water is the largest movement of a chemical substance at the surface of the Earth. Through evaporation and precipitation, water transfers much of the heat energy received by the Earth from the tropics to the poles, just as a steam heating system transfers heat from the furnace to the rooms of a house. Movements of water through the atmosphere determine the distribution of rainfall on Earth, and the annual availability of water on land is the single most important factor that determines the growth of plants (Kramer 1982). Where precipitation exceeds evapotranspiration on land, there is runoff. Runoff carries the products of mechanical and chemical weathering to the sea.

In this chapter we will examine a general outline of the global hydrologic cycle and then look briefly at some indications of past changes in the hydrologic cycle and global water balance. Finally, we will look, somewhat speculatively, at future changes in the water cycle that may accompany global climate change. These changes would have direct effects on global patterns of plant growth, the rate of rock weathering, and biogeochemical cycles. Thus, changes in the water cycle have strong implications for the future of agricultural productivity and for the social and economic well-being of human society. Significantly, widespread drought seems associated with the collapse of the early Mesopotamian civilization in the Middle East around 2200 B.C. (Weiss et al. 1993) and the disappearance of the Maya civilization in Mexico around 900 A.D. (Hodell et al. 1995).

The Global Water Cycle

The quantities of water in the global hydrologic cycle are so large that it is traditional to describe the pools and transfers in units of km^3 (Fig. 10.1). Each km^3 contains 10^{12} liters and weighs 10^{15} g. The flux of water in the water cycle may also be expressed in units of average depth. For example, if all the rainfall on land were spread evenly over the surface, each weather station would record a depth of about 70 cm/yr. Units of depth can also be used to express runoff and evaporation (e.g., Fig. 8.5). Annual evaporation from the oceans removes the equivalent of 100 cm of water each year from the surface area of the sea.

Not surprisingly, the oceans are the dominant pool in the global water cycle (Fig. 10.1). Seawater composes over 97% of all the water at the surface of the Earth. The equivalent depth of seawater is 3500 m—the mean depth of the oceans (Chapter 9). Water held in polar ice caps and in continental glaciers is the next largest contributor to the global pool. Soils contain 121,800 km^3 of water, of which about 58,100 km^3 is within the rooting zone of plants (Webb et al. 1993). Human society depends on a relatively small pool of liquid freshwater in lakes and rivers. The large pool of freshwater below the vadose zone is known as groundwater (Chapter 7). Global estimates of the volume of groundwater are poorly constrained—4,200,000 to 15,300,000 km^3—but, except as a result of human activities, groundwater is largely inaccessible to the biosphere. The pool of water in the atmosphere is tiny, equivalent to about 0.3 cm of rainfall at any given time (Eq. 3.4). Nevertheless, enormous quantities of water move through the atmosphere each year.

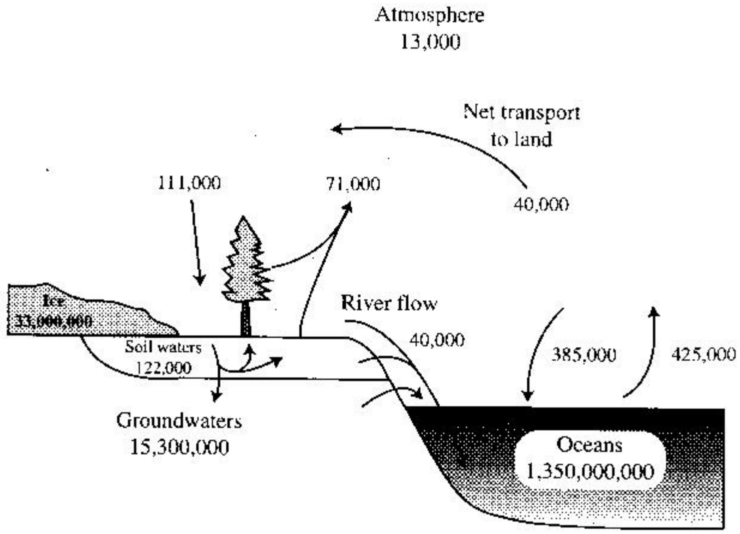

Figure 10.1 The global water cycle. Pools (km^3) and flux (km^3/yr) are mostly from Lvovitch (1973) and Chahine (1992), with some newer values as derived from the text.

Evaporation removes about 425,000 km^3 of water from the world's oceans each year. Thus, the mean residence time of ocean water with respect to the atmosphere is about 3100 years. Only about 385,000 km^3/yr of this water returns to the oceans in rainfall; the rest contributes to precipitation on land, which totals 111,000 km^3/yr. Plant transpiration and evaporation from soils return 71,000 km^3/yr to the atmosphere. Thus, with respect to precipitation inputs or evapotranspiration losses, the mean residence time of soil water is about 1 year. Owing to the excess of precipitation over evapotranspiration on land, about 40,000 km^3/yr becomes runoff.

These global average values obscure large regional differences in the water cycle. Evaporation from the oceans is not uniform, but ranges from 4 mm/day in tropical latitudes to <1 mm/day at the poles (Mitchell 1983). Although much precipitation falls at tropical latitudes, an excess of evaporation over precipitation in the tropics provides a net regional flux of water vapor to the atmosphere. Net evaporative loss accounts for the high salinity in tropical oceans (Fig. 9.3), and the movement of water vapor in the atmosphere carries latent heat to polar regions (Vonder Haar and Oort 1973).

On land the relative balance of precipitation and evaporation differs strongly between regions. In tropical rainforests, precipitation may greatly exceed evapotranspiration. Shuttleworth (1988) calculates that 50% of the rainfall becomes runoff in the Amazon rainforests (Table 8.1). In desert regions, precipitation and evapotranspiration are essentially equal, so there is no runoff and only limited recharge of groundwater (e.g., Phillips et al. 1988). As a global average, rivers carry about 1/3 of the precipitation from land to the sea. Less than 10% of precipitation becomes groundwater (Zektser and Loaiciga 1993), so the mean residence time of groundwater is over 1000 years.

The concept of *potential evapotranspiration* (PET), developed by hydrologists, expresses the maximum evapotranspiration that would be expected to occur under the climatic conditions of a particular site, assuming that water is always present in the soil and plant cover is 100%. Potential evapotranspiration is greater than the evaporation from an open pond, as a result of the plant uptake of water from the deep soil and a leaf area index >1.0 in many plant communities (Chapter 5). In tropical rainforests, PET and actual evapotranspiration (AET) are about equal (Vörösmarty et al. 1989).

In deserts, PET greatly exceeds actual AET, owing to long periods when the soils are dry. In southern New Mexico, precipitation averages about 21 cm/year, but the receipt of solar energy could potentially evaporate over 200 cm/yr from the soil (Phillips et al. 1988).

Actual evapotranspiration is often useful as a predictor of net primary production (Webb et al. 1978), decomposition (Fig. 5.15), and soil activity (Fig. 4.3). Changes in climate that affect rainfall and AET would have a dramatic effect on the biosphere. Annual variability in AET is greatest in ecosystems with low AET, reflecting large year-to-year variations in both rainfall and net primary production in deserts (Frank and Inouye 1994). Actual evapotranspiration is more constant in tundra and boreal forest ecosystems, where wet soils do not constrain the supply of water to plants. The net primary productivity of land plants (60×10^{15}g C/yr) and the actual evapotranspiration of water from land (71×10^{18} g/yr) indicate that the global average water-use efficiency of vegetation is about 1.28 mmol CO_2 fixed per mole of water lost (Eq. 5.3)—well within the range measured by physiologists studying individual leaves (Chapter 5).

The sources of water contributing to precipitation also differ greatly in different regions of the Earth. Nearly all the rainfall over the oceans is derived from the oceans. On land, much of the rainfall in maritime and monsoonal climates is also derived from evaporation from the sea. In contrast, 25–50% of the water falling in the Amazon Basin is derived from evapotranspiration within the basin, with the rest derived from long-distance atmospheric transport (Salati and Vose 1984, Eltahir and Bras 1994). Evapotranspiration in Amazon forests is maximized by deep-rooted plants (Nepstad et al. 1994), and the regional importance of evapotranspiration in the Amazon basin speaks strongly for the long-term implications of forest destruction in that region. Using a general circulation model of the Earth's climate, Lean and Warrilow (1989) show that a replacement of the Amazon rainforest by a savanna would decrease regional evaporation and precipitation and increase surface temperatures (cf. Shukla et al. 1990). Similarly, in semiarid regions, precipitation may decline as a result of the removal of vegetation, leading to soil warming (Balling 1989) and increasing desertification (Schlesinger et al. 1990, Chahine 1995, Dirmeyer and Shukla 1996). Thus, the transpiration of land plants is an important factor determining the movement of water in the hydrologic cycle and Earth's climate (Shukla and Mintz 1982, Chahine 1992).

Estimates of global riverflow range from 33,500 km^3/yr to 47,000 km^3/yr (Lvovitch 1973, Speidel and Agnew 1982). Most recent workers assume a value of about 40,000 km^3/yr (Fig. 10.1). The distribution of flow among rivers is highly skewed. The 50 largest rivers carry about 43% of the total riverflow, so reasonable estimates of the global transport of organic carbon, inorganic nutrients, and suspended sediments can be based on data from a few large rivers (e.g., Fig. 8.3).

As a result of the positions of the continents and their surface topography, relative to global climatic patterns, there are large regional differences in the delivery of runoff to the sea. The average runoff from North America is about 32 cm/yr, whereas, the average runoff from Australia, which has a large area of internal drainage and deserts, is only 4 cm/yr (Tamrazyan 1989). Thus, the delivery of dissolved and suspended sediment to the oceans varies greatly between rivers draining different continents (Table 4.7, Fig. 4.14). In the northern hemisphere, 77% of the water discharge comes from rivers in which the flow is now regulated by dams and other human structures (Dynesius and Nilsson 1994) which strongly affect the sediment transport to the sea. Postel et al. (1996) calculate that humans now use 54% of the volume of rivers globally, converting a large portion of it to water vapor as a result of irrigated agriculture.

The mean residence time of the oceans with respect to riverflow is about 34,000 years, which is 10× less dynamic than the exchange with the atmosphere. The mean residence times differ among ocean basins. The mean residence time for the Pacific Ocean with respect to riverflow is 43,700 years—significantly longer than that for the Atlantic (9600 years). This is consistent with the greater accumulation of nutrients in deep Pacific waters and a shallower carbonate compensation depth in the Pacific Ocean (Chapter 9). Despite the enormous riverflow of the Amazon, which carries about 20% of the annual freshwater delivered to the sea, continental runoff to the Atlantic ocean is less than the loss of water through evaporation. Thus, the Atlantic Ocean has a net water deficit, which accounts for its greater salinity (Fig. 9.3). Conversely, the Pacific ocean receives a greater proportion of the total freshwater returning to the sea each year. Ocean currents carry water from the Pacific and Indian oceans to the Atlantic ocean to restore the balance (Chapter 9).

Models of the Hydrologic Cycle

A variety of models have been developed to predict the movement of water through terrestrial ecosystems. Watershed models follow the fate of water received in precipitation and calculate runoff after subtraction of losses due to plant uptake (Waring et al. 1981, Moorhead et al. 1989, Ostendorf and Reynolds 1993). In these models, the soil is considered as a collection of small boxes, in which the annual input and output of water must be equal. Water entering the soil in excess of its water holding capacity is routed to the next lower soil layer or to the next downslope soil unit on the landscape via subsurface flow (Chapter 8). Models of water movement in the soil can be coupled to models of soil chemistry to predict the loss of elements in runoff (e.g., Nielsen et al. 1986, Knight et al. 1985).

A major difficulty in building these models is the calculation of plant uptake and transpiration loss. This flux is usually computed using a formulation of the basic diffusion law, in which the loss of water is determined by the gradient, or vapor pressure deficit, between plant leaves and the atmosphere. The loss is mediated by a resistance term, which includes stomatal conductance and wind speed (Chapter 5). In a model of forest hydrology, Running et al. (1989) assume that canopy conductance decreases to zero when air temperatures fall below 0°C or soil water potential declines below −1.6 MPa. Their model appears to give an accurate regional prediction of evapotranspiration and primary productivity for a variety of forest types in western Montana.

Larger scale models have been developed to assess the contribution of continental land areas to the global hydrologic cycle. For example, Vörösmarty et al. (1989) divided South America into 5700 boxes, each 1/2° × 1/2° in size. Large-scale maps of each nation were used to characterize the vegetation and soils in each box, and data from local weather stations were used to characterize the climate. A model (Fig. 10.2) is used to calculate the water balance in each unit. During periods of rainfall, soil moisture storage is allowed to increase up to a maximum water-holding capacity determined by soil texture. During dry periods, water is lost to evapotranspiration, with the rate becoming a declining fraction of PET as the soil dries.

This type of model can be coupled to other models, including general circulation models of the Earth's climate (Chapter 3), to predict global biogeochemical phenomena. For example, a monthly prediction of soil moisture content for the South American continent can be used with known relationships between soil moisture and denitrification (Potter et al. 1996; Chapter 6) to predict the loss of N_2O and the total loss of gaseous nitrogen from soils to the atmosphere. The excess water in the water balance model is routed to stream channels, where it can be used to predict the flow of the major rivers draining the continent (Russell and Miller 1990). Changes in land use and the destruction of vegetation are easily added to these models, allowing a prediction of future changes in continental-scale hydrology and biogeochemistry.

The History of the Water Cycle

As we learned in Chapter 2, water was delivered to the primitive Earth by planetesimals, meteors, and comets. The accretion of the Earth was largely complete by 3.8 billion years ago (bya). Water was released from the Earth's crust in volcanic eruptions (i.e., degassing), and as long as the Earth's temperature was >100°C, the water vapor remained in the atmosphere. When the Earth cooled <100°C, nearly all the water condensed to form the oceans. Even then, a small amount of water vapor and CO_2 remaining in the Earth's atmosphere was enough to raise the temperature of the Earth above freezing. Without this greenhouse effect the Earth might have become a frozen ball of ice—like Mars today.

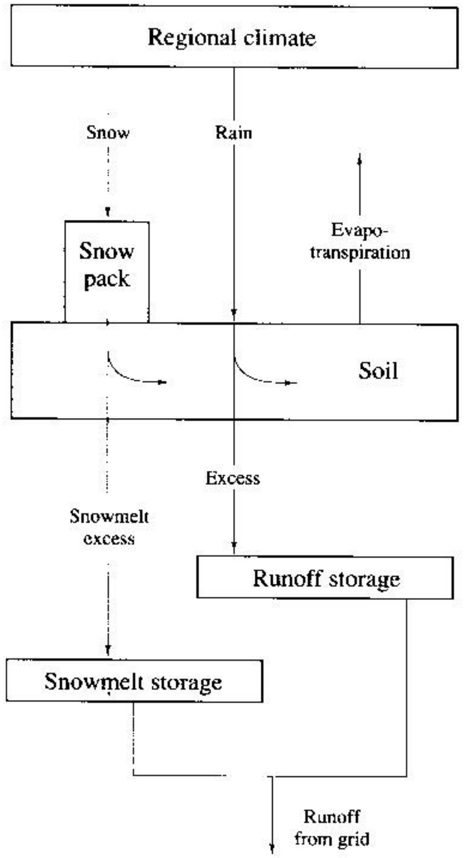

Figure 10.2 Components of a model for the hydrologic cycle of South America. From Vörösmarty et al. (1989).

There is good evidence of liquid oceans on Earth as early as 3.8 bya, and it is likely that the volume of water in the hydrologic cycle has not changed appreciably since that time. Owing to the low content of water vapor in the atmosphere, only 0.1% of the water on Earth appears to have been lost by the photolysis of H_2O in the stratosphere (Walker 1977). Much larger quantities appear to have been lost from Venus, where all water remained as vapor (Chapter 2). The total inventory of volatiles on Earth (Table 2.2) suggests that about 155 × 10^{22} g of water was degassed from its crust. The difference between this value and the total of the pools in Fig. 10.1 is largely contained in sedimentary rocks. In addition, the accumulation of O_2 in the atmosphere and in oxidized minerals of the Earth's crust suggests that about 2% of the Earth's water has been consumed by net photosynthesis through geologic time (Table 2.2).

Throughout the Earth's history, changes in relative sea level have accompanied periods of tectonic activity that increase (or decrease) the volume of submarine mountains. Changes in sea level also accompany changes in global temperature that lead to glaciations (Degens et al. 1981). The geologic record shows large changes in ocean volume during the 16 continental glaciations that occurred during the Pleistocene Epoch, extending to 2 million years ago. During the most recent glaciation, which reached a peak 18,000 years ago, $42{,}000 \times 10^3$ km^3 of seawater was sequestered in the polar ice caps (Starkel 1989). This represents 3% of the ocean volume, and it lowered the sea level about 120 m from that of present day (Fairbanks 1989). As we saw in Chapter 9, the Pleistocene glaciations are recorded in calcareous marine sediments. During periods of glaciation, the ocean was relatively rich in $H_2^{18}O$, which evaporates more slowly than $H_2^{16}O$. Calcium carbonate precipitated in these oceans shows higher values of $\delta^{18}O$, which can be used as an index of paleotemperature (Fig. 9.23).

Although many causes have been suggested, most workers now believe that ice ages are related to small variations in the Earth's orbit around the Sun (Harrington 1987). These variations lead to differences in the receipt of solar energy, particularly in polar regions. Once polar ice begins to accumulate, the cooling accelerates, because snow has a high reflectivity or albedo to incoming solar radiation. Proponents of this theory believe that the low concentrations of atmospheric CO_2 (Fig. 1.5) and the high concentrations of sulfate aerosols (Legrand et al. 1991) and atmospheric dust (Petit et al. 1990) during the last ice age were probably an effect, rather than a cause, of global cooling. These changes in the atmosphere may have reinforced the rate of cooling (Harvey 1988). At the present time, the Earth is unusually warm; we are about halfway through an interglacial period, which should end about 12,000 A.D.

Continental glaciations represent a major disruption—a loss of steady-state conditions—in Earth's water cycle. These changes in global climate appear to have affected the circulation of the oceans and the interaction of the oceans with the atmosphere (Chapter 9). Global cooling yields lower rates of evaporation, reducing the circulation of moisture through the atmosphere and reducing precipitation. One model of global climate suggests that 18,000 years ago, total precipitation was 14% lower than that of today (Gates 1976). Throughout most of the world, the area of deserts expanded, and total net primary productivity and plant biomass on land may have been much lower than today's (Shackleton 1977, J.M. Adams et al. 1990, Friedlingstein et al. 1995). Greater wind erosion of desert soils contributed to the accumulation of dust in ocean sediments, polar ice caps, and loess deposits (Chapter 3; Yung et al. 1996). The southwestern United States appears to have been an exception. Over most of this desert area, the climate of 18,000 years ago was wetter than today (Van Devender and Spaulding 1979, Wells 1983, Marion et al. 1985).

Changes in the rate of global river flow produce changes in the delivery of dissolved and suspended matter to the sea. Broecker (1982) suggests that erosion of exposed continental shelf sediments during the glacial sea-level minimum may have led to a greater nutrient content of seawater and higher marine net primary productivity in glacial times. Worsley and Davies (1979) show that deep-sea sedimentation rates throughout geologic time have been greatest during periods of relatively low sea level, when a greater area of continents is displayed.

The Water Cycle under Scenarios of Future Climate

It is widely believed that global warming could cause a melting of the polar ice caps, leading to a rise in sea level and a flooding of coastal areas during the next century. Using a variety of methods, most workers measure a rise in sea level of 1 to 2 mm/yr during the last 100 years (Gornitz 1995; Fig. 10.3). Observations of sea-level rise are complicated by the ongoing isostatic adjustments of continental elevations in response to the melting of ice

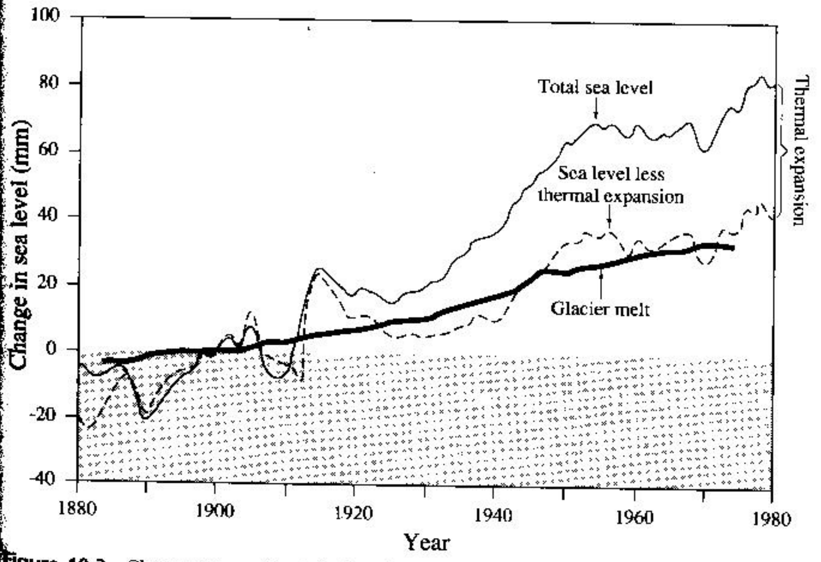

Figure 10.3 Changes in sea level during the last century (Gornitz et al. 1982), indicating the proportion due to thermal expansion of the oceans and that due to melting of glaciers. From Jacobs (1986), after Meier (1984). Copyright 1984 by the AAAS.

om the last continental glaciation. After removing this factor, Peltier and ushingham (1989) found a rise of 2.4 mm/yr from 1920 to 1970, which ıey suggest indicates global warming. Although a longer record is clearly eeded, recent measurements by the TOPEX/POSEIDON satellite suggest ıat relative sea level rose at a rate of 3.9 mm/yr globally during 1993 and 994 (Nerem 1995).

Sea surface temperatures (Strong 1989, Parrilla et al. 1994) have risen ver the last 100 years, so at least some of the rise in sea level must be ttributed to the thermal expansion of water at warmer temperatures. ome rise in sea level may also stem from human activities, including the xtraction of groundwater that is delivered to the sea by rivers (Sahagian t al. 1994). The remaining rise in sea level is likely due to the melting of nountain glaciers throughout the world—an indication of a global warm- ng trend (Oerlemans 1994). At present it is difficult to ascertain whether he volume of the massive ice sheets on Greenland and Antarctica is chang- ng (Jacobs 1992), but we can anticipate that improved measurements of ce volume by satellite remote sensing will soon aid our understanding of his portion of the water cycle (Zwally et al. 1989).

Just as the volume of a glass of water is not affected by ice cubes that may melt within it, sea level is not affected by changes in the area or volume of ice, known as *sea ice,* that is floating on the oceans' surface. Nevertheless, changes sea ice are a useful index of trends in climate that may ultimately affect the hydrologic cycle. Repeated measurements by submarines show no trend in ice thickness at the North Pole during 1977-1990 (McLaren et al. 1992), but satellite measurements using microwave sounding show that the area of Arctic sea ice is shrinking (Johannessen et al. 1995). In contrast, Antarctic sea ice appeared to show little change from 1978 to 1987 (Gloersen and Campbell 1991), although several of the ice shelves on the Antarctic Peninsula appear to have retreated during the past 50 years (Vaughan and Doake 1996).

In response to global warming, most climate models predict a more humid world, in which the movements of water in the hydrologic cycle through evaporation, precipitation, and runoff are enhanced (Neilson and Marks 1994, Loaiciga et al. 1995). Increased cloudiness may moderate the degree of warming, but a new steady state in Earth's temperature would be found at a higher value than that of today (Raval and Ramanathan 1989). Not all areas of the land will be affected equally. Most of the anticipated temperature change is confined to high latitudes, and Manabe and Wetherald (1986) show that large areas of the central United States and Asia may experience a reduction in soil moisture, leading to more arid conditions. Due to the thermal buffer capacity of water, the oceans may warm more slowly than the land surface. Because most precipitation is generated from the oceans, land areas may experience severe drought during the transient period of global warming (Rind et al. 1990, Dirmeyer and Shulka 1996).

Such changes in precipitation and temperature will lead to large-scale adjustments in the distribution of vegetation and global net primary production (Emanuel et al. 1985a, T.M. Smith et al. 1992, Neilson and Marks 1994).

Are any observed changes in the hydrologic cycle consistent with these predictions of global warming? Oltmans and Hofmann (1995) note an increase in stratospheric water vapor over Boulder, Colorado, from 1981 to 1994. A portion of this increase may be due to increasing atmospheric concentrations of methane, some of which is destroyed in the stratosphere producing water vapor (Eq. 3.21). However, the observed increase in water vapor appears to exceed that derived from CH_4, perhaps indicating an ongoing global warming trend.

Analyzing the rainfall records of 1487 weather stations, Bradley et al. (1987) found an increase in precipitation over most of the midlatitudes in the northern hemisphere in the last 30 to 40 years—consistent with changes expected for a warmer planet. Their data also show a decrease in precipitation over North Africa and the Middle East—consistent with the increasing occurrence of drought in the Sahel. In many areas precipitation also seems to be becoming more variable—droughts are more frequent—consistent with the predictions of several general circulation models of future climate (Tsonis 1996). Over much of the world, the historical record of precipitation is scanty, and we must hope that global estimates of precipitation will improve dramatically with the application of satellite remote sensing (Petty 1995). Because water vapor absorbs microwave energy, the relative transmission of microwave radiation through the atmosphere is related to water vapor content and rainfall, and satellite remote sensing of the microwave emission from Earth can measure the rainfall over large areas (e.g., Weng et al. 1994).

Greater precipitation should lead to greater runoff from land (Miller and Russell 1992). Probst and Tardy (1987) found a 3% increase in streamflow in major world rivers over the last 65 years. This increased streamflow may be an indication of global climate change, but it may also relate to the human destruction of vegetation leading to greater runoff (Chapter 8). We might also speculate that greater streamflow is expected due to greater water-use efficiency by vegetation growing in a high-CO_2 atmosphere (Chapter 5; Idso and Brazel 1984). Finally, greater runoff may be due to the surprising decline in evaporation rates reported over a large proportion of the United States and Russia during the last several decades (Peterson et al. 1995).

The historical pattern of runoff for each continent and for the world as a whole shows a cyclic pattern (Fig. 10.4). The cycles for the continents are not synchronous, so the cycles in the global record are "damped," relative to those on each continent. In sum, the recent increases in water vapor, precipitation, and streamflow are consistent with predicted changes in the water cycle with global warming, but such observations must be

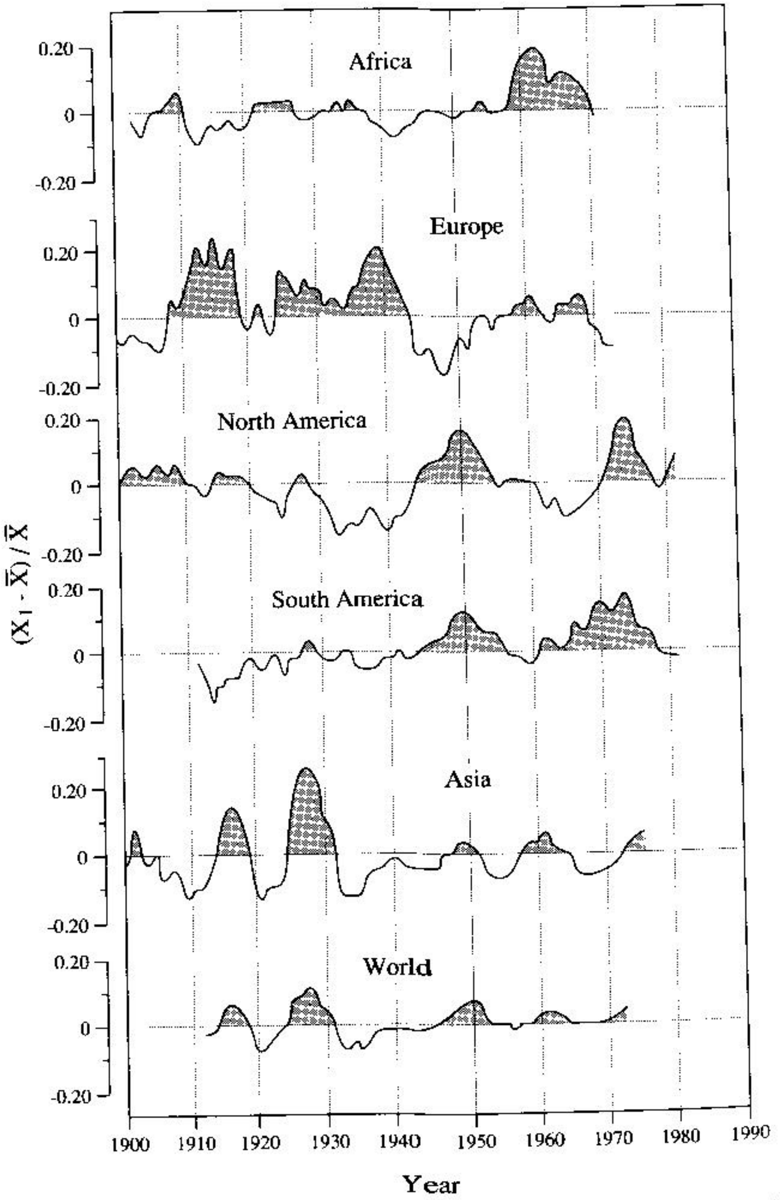

Figure 10.4 A comparison of fluctuations in riverflow draining various continents and averaged for the world. Variation is expressed as the difference between an annual value and the long-term mean, as a fraction of the long-term mean. From Probst and Tardy (1987).

evaluated in the context of long-term cycles in climate that have occurred through geologic time.

Summary

Through evaporation and precipitation the hydrologic cycle transfers water and heat throughout the global system. Receipt of water in precipitation is one of the primary factors controlling net primary production on land. Changes in the hydrologic cycle through geologic time are associated with changes in global temperature. All evidence suggests that movements in the hydrologic cycle were slower in glacial time, and that they would be likely to increase with global warming. Movements of water on the surface of the Earth affect the rate of rock weathering and other biogeochemical phenomena.

Recommended Readings

Baumgartner, A. and E. Reichel. 1975. *The World Water Balance.* R. Olenburg, Munich.
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