1

The Hydrological Cycle

1.1 Overview

The hydrological cycle describes the continuous movement of water above, on and below the surface of the Earth. It is a conceptual model that describes the storage and movement of water between the *biosphere* (the global sum of all ecosystems, sometimes called the zone of life on Earth), the *atmosphere* (the air surrounding the Earth, which is a mixture of gases, mainly nitrogen (about 80%) and oxygen (about 20%) with other minor gases), the *cryosphere* (the areas of snow and ice), the *lithosphere* (the rigid outermost shell of the Earth, comprising the crust and a portion of the upper mantle), the *anthroposphere* (the effect of human beings on the Earth system) and the *hydrosphere* (see Table 1.1).

Models of the biosphere are often referred to as *land surface parameterization schemes* (LSPs) or *soil–vegetation–atmosphere transfer schemes* (SVATs). An example of an SVAT is described by Sellers et al. (1986). The water on the Earth's surface occurs as streams, lakes and wetlands in addition to the sea. Surface water also includes the solid forms of precipitation, namely snow and ice. The water below the surface of the Earth is ground water.

Most of the energy leaves the ocean surface in the form of latent heat in water vapour, but this is not necessarily the case for land surfaces. Hence maritime air masses are different to continental air masses. The atmosphere and oceans are strongly coupled by the exchange of energy, water vapour, momentum at their interface, and precipitation. The oceans represent an enormous reservoir for stored energy and are denser than the atmosphere, having a larger mechanical inertia. Therefore ocean currents are much slower than atmospheric flows. The atmosphere is heated from below by the Sun's energy intercepted by the underlying surface, whereas the oceans are heated from above. Lakes, rivers and underground water can have significant hydrometeorological and hydroclimatological significance in continental regions. The hydrological cycle is represented by the simplified diagram in Figure 1.1.

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Table 1.1 Water in the hydrosphere and the distribution of fresh water on the Earth (from Martinec, 1985)

(a) Distribution of water in the hydrosphere

Forms of water present	Water volume (10^6 km^3)	As %
Oceans, seas	1348	97.4
Polar ice, sea ice, glaciers	28	2.0
Surface water, ground water, atmospheric water	8	0.6
Total	1384	100.0
Total fresh water	36	2.6

(b) Distribution of fresh water on Earth

	Water volume (10^6km^3)		As %	
Forms of water present	*	†	*	†
Polar ice, glaciers	24.8	27.9	76.93	77.24
Soil moisture	0.09	0.06	0.28	0.17
Ground water within reach	3.6	3.56	11.17	9.85
Deep ground water	3.6	4.46	11.17	12.35
Lakes and rivers	0.132	0.127	0.41	0.35
Atmosphere	0.014	0.014	0.04	0.04
Total	32.236	36.121	100.0	100.0

* Based on Volker (1970).
† Based on Dracos (1980), referred to in Baumgartner and Reichel (1975).

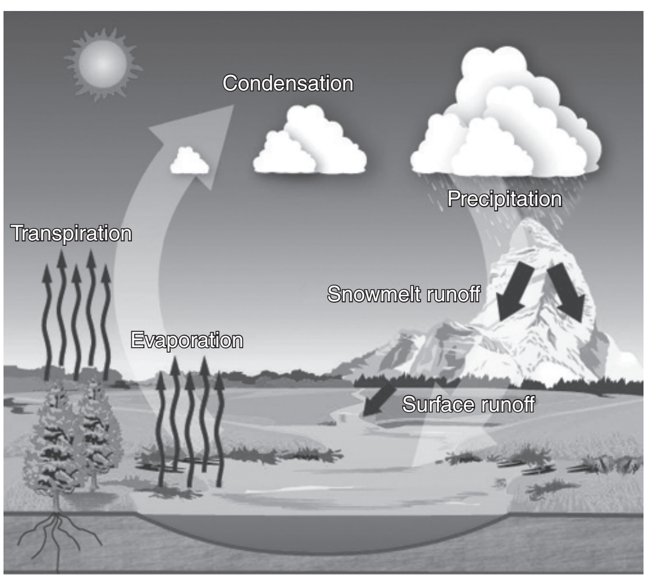

Figure 1.1 Simplified representation of the hydrological cycle (NWS Jetstream NOAA, USA, www.srh.noaa.gov/jetstream/atmos/hydro.htm) (*see plate section for colour representation of this figure*)

1.2 Processes comprising the hydrological cycle

There are many processes involved in the hydrological cycle, the most important of which are as follows:

- *Evaporation* is the change of state from liquid water to vapour. The energy to achieve this may come from the Sun, the atmosphere itself, the Earth or human activity.
- *Transpiration* is the evaporation of water from plants through the small openings found on the underside of leaves (known as stomata). In most plants, transpiration is a passive process largely controlled by the humidity of the atmosphere and the moisture content of the soil. Only 1% of the transpired water passing through a plant is used by the plant to grow, with the rest of the water being passed into the atmosphere. Evaporation and transpiration return water to the atmosphere at rates which vary according to the climatic conditions.
- *Condensation* is the process whereby water vapour in the atmosphere is changed into liquid water as clouds and dew. This depends upon the air temperature and the dew point temperature. The dew point temperature is the temperature at which the air, as it is cooled, becomes saturated and dew can form. Any additional cooling causes water vapour to condense. When the air temperature and the dew point temperature are equal, mist and fog occur. Since water vapour has a higher energy level than liquid water, when condensation occurs the excess energy is released in the form of heat. When tiny condensation particles, through collision or coalescence with each other, grow too large for the ascending air to support them, they fall to the surface of the Earth as precipitation (Chapter 2). Precipitation is the primary way fresh water reaches the Earth's surface, and on average the Earth receives about 980 mm each year over both the oceans and the land.
- *Infiltration* of water into the land surface occurs if the ground is not saturated, or contains cracks or fissures. The flow of water into the ground may lead to the recharge of aquifers, or may move through unsaturated zones to discharge into rivers, lakes or the seas. Between storm or snowmelt periods, stream flow is sustained by discharge from the ground water systems. If storms are intense, most water reaches streams rapidly. Indeed, if the water table – the boundary between the saturated and unsaturated zones – rises to the land surface, overland flow may occur.
- The *residence time* of water in parts of the hydrological cycle is the average time a water molecule will spend in a particular area. These times are given in Table 1.2. Note that ground water can spend over 10,000 years beneath the surface of the Earth before leaving, whereas water stored in the soil remains there very briefly. After water evaporates, its residence time in the atmosphere is about nine days before it condenses and falls to the surface of the Earth as precipitation. Residence times can be estimated in two ways. The first and more common method is to use the principle of conservation of mass, assuming the amount of water in a given store is roughly constant. The residence time is derived by dividing the volume of water in the store by the rate by which water either enters or leaves the store. The second method, for ground water, is via isotropic techniques. These techniques use either in-stream tracer injection combined with modelling, or measurements of naturally occurring tracers such as radon-222 (see for example Lamontagne and Cook, 2007).

Table 1.2 Average residence times for specific stores (see for example www.physicalgeography.net/fundamentals/8b.html)

Reservoir	Average residence time
Antarctica	20,000 years
Oceans	3,200 years
Glaciers	20 to 100 years
Seasonal snow cover	2 to 6 months
Soil moisture	1 to 2 months
Ground water shallow	100 to 200 years
Ground water deep	10,000 years
Lakes	50 to 100 years
Rivers	2 to 6 months
Atmosphere	9 days

- *Human activities* release tiny particles (aerosols) into the atmosphere, which may enhance scattering and absorption of solar radiation. They also produce brighter clouds that are less efficient at releasing precipitation. These aerosol effects can lead to a weaker hydrological cycle, which connects directly to the availability and quality of fresh water (see Ramanathan et al., 2001).

1.3 Global influences on the hydrological cycle

Differential heating by the Sun is the primary cause of the general circulation of the atmosphere. There are a number of regional differences which influence the hydrological cycle in addition to the relative position of the Sun and the Earth. There are latitudinal differences in solar input brought about by the rotation of the Earth. These cause seasonal changes in the circulation patterns, and produce a regular diurnal cycle in the longitude.

The fluxes of surface latent and sensible heat are different between continental and oceanic surfaces. Also continental topography varies in ways which significantly impact the atmosphere. Changes in land cover, atmospheric composition and sea surface temperature alter the hydrological cycle both persistently and on a temporary basis.

Clouds transport substantial amounts of water around the atmosphere. Consequently they have a major impact on the absorption of solar radiation and modify surface energy balance. Some tall clouds tend to shade and inhibit solar radiation reaching the ground, whereas high clouds inhibit the loss of long wave radiation.

The peak zonal mean precipitable water is situated at 10°N for the overall mean (Figure 1.2a) and for the mean over sea (Figure 1.2c). The zonal mean precipitable water over land (Figure 1.2b) is nearly symmetrical about the equator for the annual mean, and the winter (DJF) mean is close to the mirror image of the summer (JJA) mean between 40°S and 40°N. The water vapour content of the atmosphere is highly sensitive to the temperature through the saturation vapour pressure, and the temperature decreases towards the upper atmosphere. The SI unit of pressure is the

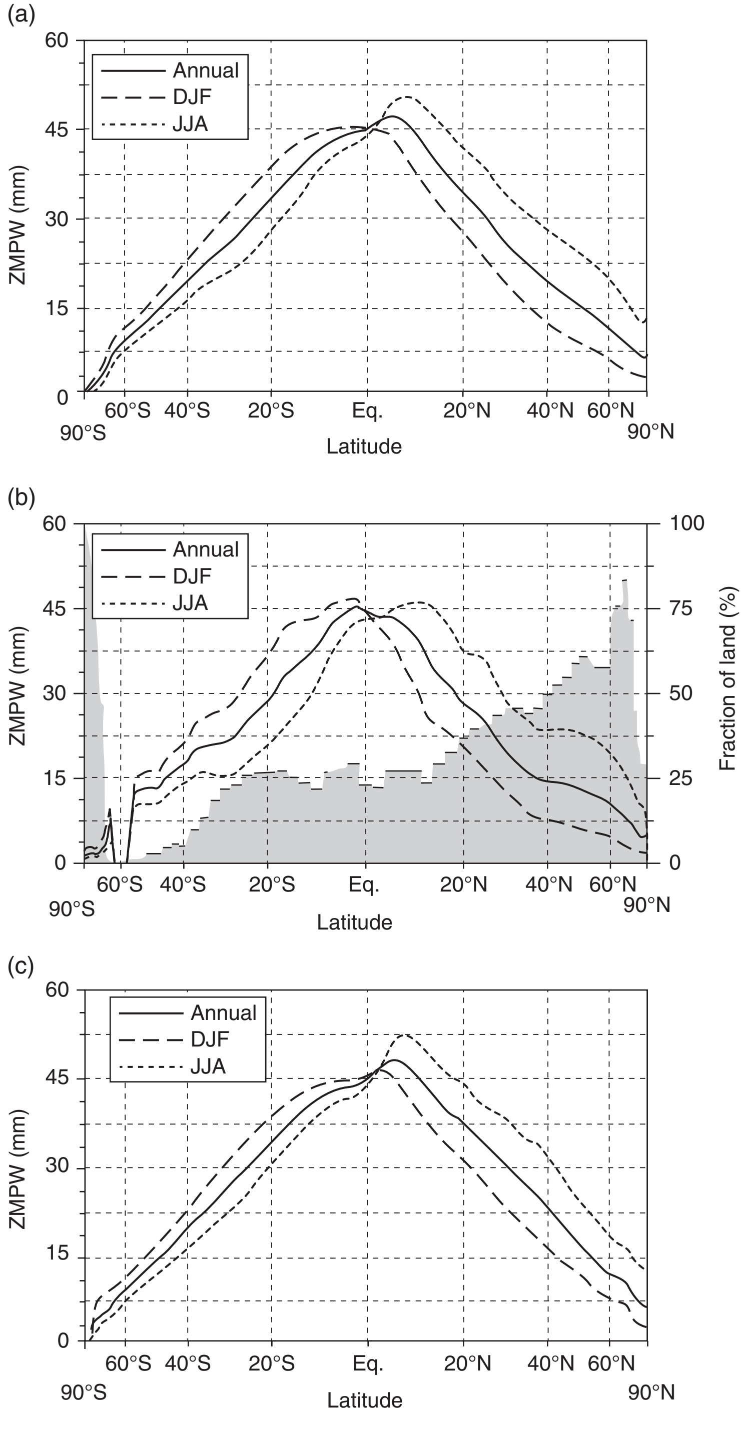

Figure 1.2 Meridional distribution of zonal mean precipitable water (mm): (a) over land and sea, (b) mean over land only, and (c) mean over sea only. Annual mean, December-January-February (DJF) mean, and June-July-August (JJA) mean, for 4 years from 1989 to 1992 (from Oki, 1999)

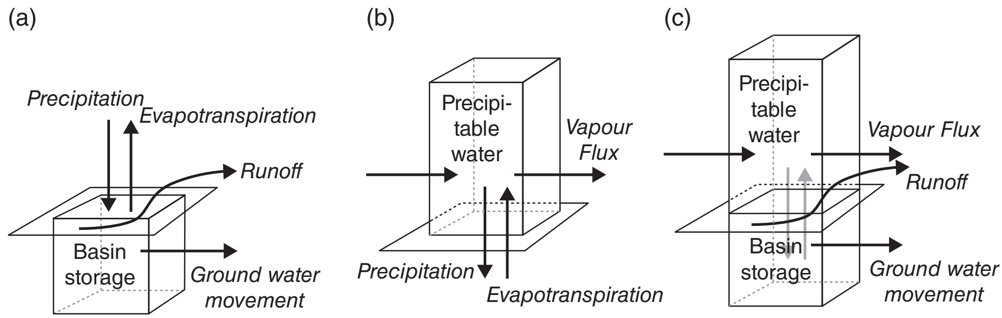

Figure 1.3 Illustrating (a) terrestrial water balance, (b) atmospheric water balance and (c) combined atmospheric–terrestrial water balance (from Oki, 1999)

pascal (Pa), and atmospheric pressure at mean sea level is approximately 10^5 Pa or 1000 hectopascals (hPa). More than 50% of the water vapour is concentrated below the 850 hPa surface, and more than 90% is confined to the layer below 500 hPa (see Peixoto and Oort, 1992).

1.4 Water balance

Water balance at the land surface has generally been estimated using ground observations such as precipitation, water storage in lakes and ground water. This is described by

$$\frac{\partial S}{\partial t} = -\nabla_{\mathrm{H}} \cdot \mathbf{R}_0 - \nabla_{\mathrm{H}} \cdot \mathbf{R}_{\mathrm{u}} - (E - P) \tag{1.1}$$

where S represents the water storage within the area, $\mathbf{R}_0$ is surface runoff, $\mathbf{R}_{\mathrm{u}}$ is the ground water movement, E is evapotranspiration and P is precipitation; ∇_{H} is horizontal divergence. S includes snow accumulation in addition to soil moisture, ground water and surface water storage, including retention water (see Oki, 1999).

The atmospheric water balance is described by

$$\frac{\partial W}{\partial t} + \frac{\partial W_{\mathrm{c}}}{\partial t} = -\nabla_{\mathrm{H}} \cdot \mathbf{Q} - \nabla_{\mathrm{H}} \cdot \mathbf{Q}_{\mathrm{c}} + (E - P) \tag{1.2}$$

where W represents precipitable water in vapour in a column, W_{c} is the column storage of liquid and solid water, $\mathbf{Q}$ is the vertically integrated two-dimensional water vapour flux, and $\mathbf{Q}_{\mathrm{c}}$ is the vertically integrated two-dimensional water flux in the liquid and solid phases. Both the land surface and the atmospheric water balances are summarized in Figure 1.3.

1.5 Impact of aerosols on the hydrological cycle

Aerosol particles (liquid and solid particles, usually other than natural water droplets) are an important part of the water cycle as they serve as condensation nuclei for the formation of cloud droplets as well as scattering and absorbing solar radiation.

Ramanathan et al. (2001) have described how this occurs. Atmospheric aerosols range in size from hundredths of a micrometre to many tens of micrometres. They derive from many sources, namely the Earth's surface, oceans, volcanoes and the biosphere. Many aerosols derive from human activity. Large amounts of dust from major deserts, such as the Sahara, produce massive amounts of aerosol. Sea salt produced by bursting air bubbles and winds is the largest natural flux of aerosol mass into the atmosphere, although much of this mass is large particles that are not transported very far. Volcanoes can inject large amounts of particles and gases into the atmosphere, and if they reach the stratosphere they are removed more slowly than if they reside only in the troposphere. The formation of sulphates from sulphur gases, produced from marine phytoplankton, continental biota and the burning of fossil fuels, is an important source of aerosols.

Increases in aerosols generally greater in size than a few hundredths of a micrometre, referred to as cloud condensation nuclei (CCN), increase the droplet number concentration in clouds, which increases cloud extent and leads to global cooling. If the amount of water available for condensation in the cloud is not changed, this means that there will be a greater number of smaller drops, which are less likely to grow to sufficient size to fall out as precipitation (see Chapter 2); thus clouds last longer, again contributing to cooling. The cooling of the surface through increased reflection of solar energy, and the reduced efficiency of clouds in producing precipitation, resulting from increases in aerosol, will weaken the hydrological cycle.

1.6 Coupled models for the hydrological cycle

Studies of the hydrological cycle usually involve feedbacks between atmospheric, ecological and hydrological systems, as well as human society. Often the feedbacks between systems produce unanticipated responses. Hence the coupling of different compartments of the Earth system is a challenge to the numerical modelling community.

Imposing a boundary between components of the modelled hydro-geo-biosphere system is not feasible. Observations of two or more state variables that are coupled cannot be modelled simultaneously without the processes that couple them also being included in the model.

Over the past two decades advances have been made in interfacing different Earth system components within hydrological models (see for example Bronstert et al., 2005). It is apparent that there is a need for hydrology to interact not only with atmospheric sciences but also with soil sciences, geochemistry, biology and even sociology.

Scale issues are important. Processes that dominate system behaviour at small scales may become irrelevant at large scales, and new processes may emerge as being important to the change in scale. In addition, the spatial variability of fluxes such as rainfall, of properties such as hydraulic conductivity, and of state variables such as soil humidity often leads to unexpected system responses. Also land surface and subsurface states, particularly soil moisture, affect the persistence of drier or wetter atmospheric conditions. This is of importance for the occurrence of large floods or droughts. Finally human feedbacks are as important as natural feedbacks.

1.7 Global Energy and Water Cycle Exchanges Project (GEWEX)

GEWEX is an integrated programme of research, observations and science activities that focuses on the atmospheric, terrestrial, radiative, hydrological, and coupled processes and interactions that determine the global and regional hydrological cycle, radiation and energy transitions and their involvement in climate change. It is the core project in the World Climate Research Programme (WCRP) which is concerned with studying the dynamics and thermodynamics of the atmosphere, its interactions with the Earth's surface, and its effects on the global energy and water cycle.

The goal of GEWEX is to reproduce and predict, by means of suitable numerical models, the variations of the global hydrological cycle, its impact on atmospheric and surface dynamics, and variations in regional hydrological processes and water resources and their response to changes in the environment, such as the increase in greenhouse gases. GEWEX will provide an order of magnitude improvement in the ability to model global precipitation and evaporation, as well as accurate assessment of the sensitivity of atmospheric radiation and clouds to climate change.

GEWEX plays a central role in the interaction of WCRP with many international organizations and programmes dealing with climate observations. As part of WCRP's input to the Group on Earth Observations (GEO) Global Earth Observation System of Systems (GEOSS), GEWEX brings its unique expertise in two specific societal benefit areas: climate and water. GEWEX leads in the development of plans for the global data reprocessing effort and observation strategy, and serves as a demonstration project for future climate change understanding, using observational networks in GEOSS. GEWEX supports the Integrated Global Water Cycle Observations (IGWCO) theme.

Clouds cover about 70% of the Earth's surface. The GEWEX Cloud Assessment was initiated in 2005, and provides the first coordinated intercomparison of publicly available global cloud products retrieved from measurements of multispectral imagers, IR sounders and lidar.

1.8 Flooding

Where land not normally covered by water becomes covered by water, a flood occurs. There are many sources of flooding as follows:

- *River (fluvial) flooding*: this occurs when a river cannot cope with the amount of water entering it. Over 12% of the population of the United Kingdom live on fluvial floodplains or areas identified as being subject to the risk of coastal flooding. More than 150 million people and gross domestic product (GDP) of more than $1300 billion are exposed to river flooding each year around the world.
- *Coastal flooding*: weather and tidal conditions can increase sea levels. The frequency and severity of this type of flooding are predicted to increase.
- *Surface water (pluvial) flooding*: this happens when there is heavy rainfall on ground that is already saturated, or on paved areas where drainage is poor.
- *Ground water flooding*: when rainfall causes the water that is naturally stored underground to rise to the surface it can flood low lying areas.
- *Drain and sewer (urban) flooding*: this can occur during heavy rain when drains have become blocked or full.

Jongman et al. (2012) suggested that the potential effects of flooding increased between 1970 and 2010. Three-quarters of those who were affected by river flooding in 2010 lived in Asia. Only 9% lived in Europe, although, after Asia, more people were exposed to river flooding in Europe than anywhere else. The population exposed to river flooding in Europe was predicted to fall between now and 2050. Globally, economic losses from flooding exceeded $19 billion in 2012, and are rising rapidly (Ward et al., 2013).

One major effect of climate change is the increased risk of flooding, which could cause serious loss of life and property in many parts of the world. Recent work by Hirabayashi et al. (2013) uses the output from 11 different climate models to estimate the increased global risk of floods due to climate change. Using a river routing model to calculate future river flows and flooding areas, they were able to predict that floods will become more frequent over 42% of the Earth's surface. Areas including South East Asia, India, eastern Africa and the northern Andes are likely to be most impacted. Floods that used to occur every 100 years are predicted to start occurring every 5–25 years in many areas

In the following chapters we discuss these types of floods and how they are measured, modelled and forecast.

Summary of key points in this chapter

1. The hydrological cycle describes the continuous movement of water above, on and below the surface of the Earth.
2. Models of the biosphere are often referred to as land surface parameterization schemes (LSPs) or soil–vegetation–atmosphere transfer schemes (SVATs).
3. Energy leaves the ocean surface in the form of latent heat in water vapour, and the atmosphere and oceans are strongly coupled by the exchange of energy, water vapour, momentum at their interface, and precipitation.
4. The atmosphere is heated from below by the Sun's energy intercepted by the underlying surface, whereas the oceans are heated from above.
5. The most important processes involved in the hydrological cycle are evaporation, transpiration, condensation and infiltration.
6. The residence times of water in parts of the hydrological cycle may be estimated using the principle of conservation of mass or, for ground water, isotropic techniques.
7. Aerosols are tiny particles in the atmosphere which may enhance the scattering and absorption of solar radiation, produce brighter clouds, and weaken the hydrological cycle.
8. Differential heating by the Sun is the primary cause of the general circulation of the atmosphere, and fluxes of surface latent and sensible heat are different between continental and oceanic surfaces. Clouds transport substantial amounts of water around the atmosphere.
9. Water balance equations describe the movement of water over the land, within the ground, in the atmosphere, and between the atmosphere and the land.
10. Sources of flooding are river (fluvial), coastal, surface water (pluvial), ground water, and drain and sewer (urban) surcharging.

Problems

1. Describe the structure of the hydrological cycle, noting the continuous movement of water.
2. What is the difference between maritime and continental air masses?
3. Briefly describe the processes comprising the hydrological cycle.
4. Describe the residence times of water in the components of the hydrological cycle, and how they may be estimated.
5. Describe the zonal mean precipitation with latitude in summer and winter.
6. Give the equation describing the atmospheric water balance.
7. Outline the nature of aerosols in the atmosphere, and their role in the hydrological cycle.

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