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Part I

Understanding ‘water’

1

Climate change and the global water cycle

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1.1 Background

The global water cycle links climate and hydrology and plays a critical role in the climate system. The perception that humans are responsible for an inevitable change in the climate is gaining widespread acceptance. In particular, the most recent report of the Intergovernmental Panel on Climate Change (IPCC FAR, 2007) affirms that climate change is already taking place and that its main cause involves human activities. Although the spectre of climate change is leading to many concerns about human livelihoods and ecosystem sustainability, nowhere are such concerns greater than those related to the impacts of this change on freshwater resources and their implications for society. Water-cycle scientists are considering the implications of climate change for the water cycle by addressing large-scale questions such as ‘Is the global water cycle accelerating or intensifying?’, as well as questions about local and watershed scale impacts.

Water plays a critical role in the welfare of societies around the world and affects the livelihood of every human. It is essential for the maintenance of life. Virtually all living fauna and flora consist of a significant proportion of water and must maintain those proportions for life to continue. More generally, water is an essential input that strongly affects the productivity and success of a number of economic sectors, from agriculture to energy production. It is also a means of transportation and a source of clean energy. In short, the survival of every human, every region, and every society depends on having access to a share of the world’s water through the global water cycle.

The unique thermodynamic properties of water reinforce the linkages between water and energy in the environment. At sea-level barometric pressure and 0 °C, a condition frequently experienced at the Earth’s surface, water can exist in equilibrium in solid, liquid, and gas phases. In situations when temperatures are colder than this ‘triple point’, cryospheric processes (solid–gas or solid–liquid) dominate, while in situations with temperatures warmer than 0 °C, liquid–gas processes dominate. Phase changes from solid to liquid to gas (or vice versa) involve the absorption (or release) of latent heat. Climate change is expected to reduce the areas and time periods where cryospheric processes dominate and

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lead to changes in ice cover and rain-to-snow ratios at mid to high latitudes. The consequences of this phase change are arguably the most important effects that a change in climate will have on the global water cycle.

Water is the third most abundant gas in the atmosphere. It is also a major component of the Earth's surface since the world's oceans cover 70.7% of our planet's surface area. Water serves as a major control on energy in the climate system. For example, atmospheric water is responsible for the formation of clouds which alter the energy budget at the Earth's surface. The formation and fallout of precipitation results in the release of latent heat to the atmosphere and supplies water to the Earth's surface. Water evaporates from both ocean and land surfaces into the atmosphere where it increases the atmospheric water vapour, which in turn absorbs outgoing radiation from the Earth's surface and maintains the mean global temperature well above the values that would occur if the atmosphere were completely dry. The movement and storage of water throughout the Earth–atmosphere system, which is often referred to as the global water cycle, represent the integration of both the water supply and energy aspects of this cycle.

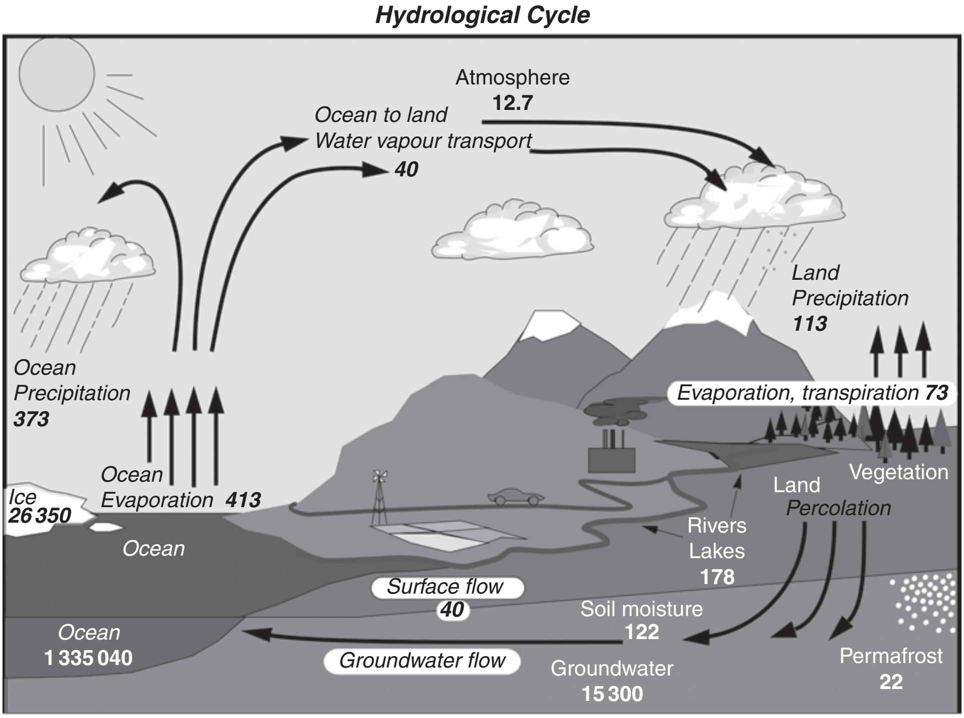
It should be noted that climate change is not the only influence on water availability and the global water cycle. The availability of water is also affected by:

- population size and growth, which has a large impact on the demand for water (Vorosmarty *et al*., 2000);
- movement of people from rural environments to urban environments, which leads to shifts in water use patterns;
- higher demands for food security, which increases the requirement for irrigation water;
- pollution from industrial and agricultural applications, which affects the quality of water available for domestic and industrial use; and
- land use changes which affect the local cycling of water.

These topics are dealt with in depth elsewhere in this book but are mentioned here so that climate change influences can be considered in the context of the other anthropogenic factors influencing water availability and use. The remainder of this chapter focuses on the linkages between changes in the climate system and the water cycle, and discusses the consequences of these anticipated changes for the freshwater resources of the Earth.

1.2 The global water cycle and its sensitivity to climate change

The global water cycle redistributes water from oceans to land through atmospheric circulation and then back to the ocean primarily through surface and sub-surface flows (runoff). Annually, there is a net flux of moisture from the world's oceans to the atmosphere as a result of the excess evaporation over oceans and net flux of water from the air to the land because land precipitation exceeds land evaporation when averaged over the globe. Evaporation, atmospheric moisture transport, and precipitation are key processes and fluxes for the movement of moisture from source to sink regions. Figure 1.1 shows the



Units: Thousand cubic km for storage, and *thousand cubic km/yr* for exchanges

Figure 1.1. The global water cycle (after Trenberth *et al*., 2007). The numbers represent (in thousands of cubic kilometres) estimates of the amount of water held in each storage component and annual net flux.

various processes and stores that constitute the global water cycle which is responsible for the distribution of precipitation and the world's water supplies. Energy to keep the cycle operating is supplied by the sun's heat which creates an equator-to-pole atmospheric pressure differential that maintains the atmospheric circulation and provides the energy required for the phase transitions between the solid, liquid, and gaseous phases. The individual variables that are needed to characterise the global water cycle and their sensitivity to climate change are described below.

1.2.1 Water vapour

Water vapour is one of the major constituents of the Earth's atmosphere and acts as an important greenhouse gas. Although the atmosphere holds only approximately 12 km^3 of moisture at any instant (which is roughly 0.0007% of the water stored in the Earth system), a much larger volume of moisture moves through the atmosphere over the annual cycle, entering through evaporative processes at the surface and leaving through the fallout of precipitation.

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More information

The maximum amount of water vapour that can be present in the atmosphere is related to the air temperature through the Clausius–Clapeyron equation (Hess, 1959):

$$\ln e_{\mathrm{s}} = -\frac{m_{\mathrm{v}} L_{12}}{R^{*} \times T} + \text{constant},$$

where e_{s} is the saturation vapour pressure,

m_{v} is the mean molecular weight of water vapour,
L_{12} is the latent heat released (or absorbed) in going from Phase 1 to Phase 2,
R^{*} is the universal gas constant, and
T is the absolute temperature.

Application of this equation shows that the atmosphere over areas of the Earth with higher temperatures can hold more water vapour than the atmosphere over areas with cooler temperatures. As atmospheric temperatures increase due to climate change, the potential for the atmosphere to hold moisture will also increase. Some investigators suggest that the potential for heavy rain events will increase as the vapour pressure of the atmosphere increases and more water is held in atmospheric storage. Higher atmospheric concentrations of water vapour will also lead to the capture of more outgoing radiation and further atmospheric warming. It is not clear how successfully models account for the greenhouse gas effects of water vapour.

1.2.2 Clouds

Clouds are part of the atmospheric component of the water cycle. In general they delineate the volume of air where saturation and condensation are occurring. As a result of saturation, which usually arises from topographic lifting, convective overturning, or synoptic scale uplift, condensation occurs on cloud condensation nuclei, leading to the formation of cloud droplets or ice particles, and causing the saturated volume to become opaque and a cloud forms as the concentration of these particles and droplets increases.

Clouds play an important role in the climate system because they reflect incoming solar radiation back to the atmosphere and serve as ‘incubators’ for the formation of precipitation. However, the ephemeral nature of clouds makes it very difficult to model or even measure their distribution and cumulative impact. This is particularly true for climate models, where there is a large mismatch between the scale of clouds and the size of a model grid square. One of the major unresolved uncertainties in climate change projections relates to simulating cloud formation processes and distribution. As a result of the cloud–climate feedback, models which predict lower cloud coverage with increasing atmospheric CO_2 can be expected to have higher global temperature increases, while those with higher cloud cover are likely to have smaller increases.

1.2.3 Precipitation

Precipitation is a critical source of renewable freshwater for the Earth. In an unpolluted atmosphere, precipitation is formed by the condensation of water molecules on small,

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chemically benign condensation nuclei. Precipitation events occur on a range of space and time scales. The amount of precipitation that falls on an annual basis in a particular country represents the renewable freshwater that is available to that country. Estimates of annual precipitation over the Earth's land areas vary from 113 500 km^3 to 120 000 km^3 (Shiklomanov and Rodda, 2003).

Precipitation that falls on land may return to the atmosphere through evapotranspiration, runs off eventually into rivers, and into the ocean or infiltrates into the groundwater system. In temperate, moist climates roughly one-third of the water runs off, one-third is evaporated back into the atmosphere, and one-third infiltrates into the ground. However, in drier climates the proportion (but not necessarily the total) of the moisture that is returned to the atmosphere through evaporation is larger. The processes responsible for the formation of precipitation vary according to location and season, and explain the large spatial variability in the distribution of precipitation. Precipitation amounts are the integrated result of a range of processes operating on many scales, ranging from updrafts in large synoptic scale cyclones to in-cloud processes and micro-scale drop–drop interactions. The large spatial variability of precipitation, and the associated non-uniform supply of freshwater, leads to parts of the world where certain nations have abundant water and others have perpetual water stress. In practice, rivers are also a source of fresh water because they transport water from source countries to downstream countries and finally to the ocean. Bates *et al*. (2008) indicate that there is general consensus among models that, as the climate warms, precipitation amounts in general will increase at higher latitudes and decrease at lower latitudes.

Skill in simulating and predicting precipitation is still being developed. Processes governing the formation of precipitation depend on the barometric pressure and temperature where it is occurring. In general, climate models tend to produce precipitation most accurately for processes with spatial scales larger than (or equal to) the spatial resolution of the climate model. The processes responsible for intense convective events on small spatial scales – that often result in extreme precipitation events – are often highly parameterised in these models, to the point where they may average out the extreme events. The latent heat released by precipitation influences the energy balance of the atmosphere, especially in the tropics, making this issue a critical one for precipitation research. To some extent this issue also limits the utility of current model outputs in the study of extreme events.

Precipitation that falls as snow is particularly sensitive to climate warming. Snow accounts for as much as 40%–70% of the total precipitation that falls at some high-latitude locations. Snow forms in the upper layers of many mid- and high-latitude clouds, even in summer, but it melts and is converted into rain as it falls through a melting zone. At higher latitudes, where temperatures drop considerably in autumn and winter, the melting layer disappears and nearly all of the precipitation falls as snow. Snow accumulates on the Earth's surface over the winter season, forming a snow pack on the surface or augmenting polar and mountain glaciers. Warming associated with climate change will have a significant effect on snowfall patterns, with more of the late autumn and spring precipitation at

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mid- and high-latitudes falling as rain instead of snow, leading to significant shifts in precipitation type and the earlier melt of the snow pack in the spring (Dettinger and Cayan, 1995; Stewart *et al*., 2005).

1.2.4 Runoff and surface water storage

Runoff is generated when rain reaches the surface and either flows over the surface or, more commonly, trickles through a network of small surface channels and shallow subsurface layers to a river or stream. Overland runoff occurs if the rain is falling on ground that is unable to absorb this quantity of water, perhaps because it is rock or pavement with very low porosity or it is fully saturated or frozen, or the rain is too intense for the ground to absorb. Precipitation outputs from global models are often too coarse (e.g. spatial scales of 50 km or larger) to use reliably in hydrologic models for runoff estimation. According to hydrological studies, rain intensity needs to be above a certain threshold before it produces significant runoff (Schaake, J., personal communication). This is an important factor when assessing how much runoff is likely to occur as a result of rainfall predicted by large-scale climate models; these models work on grid-square averages and so will frequently produce rainfall rates that are below runoff thresholds, even though runoff would in fact occur at some places within the grid square. Improved downscaling techniques (see Section 1.5) are needed to preserve the characteristics of high-intensity rainfall events and ensure realistic amounts of runoff are generated from climate models.

The average amount of water stored in streams globally is estimated to be 2253 km^3 (Shiklomanov and Rodda, 2003). This water is continually being recycled back to the oceans with a net annual outflow estimated to be 37 000 km^3. Over the past two decades changes have been observed in the seasonality of streamflow in watersheds where snowmelt supplies a significant portion of the streamflow; in general, winter flows for rivers in the western USA have increased and peak flows have shifted to earlier in the spring (Stewart *et al*., 2005). According to their analysis, warmer winter temperatures are leading to earlier snowmelt seasons which, in turn, are leading to earlier peak flows in the spring and decreasing flows during the summer months. Changes are also occurring in the upper parts of some mountain watersheds due to earlier and more prolonged glacier melt.

Mauer (2004) reported that long-term stream discharge records show that most stations (but not all) in Africa and South-east Asia have a trend toward decreasing flows. In Europe and North America the number of stations with a significant trend of increasing discharge was greater than those with a significant decreasing trend. In some areas where rain is the primary cause of floods there has been an increasing frequency of floods. The observational analyses of trends in runoff and other aspects of the global water cycle are hampered by the extent and quality of suitable observations available through global data centres such as the Global Runoff Data Centre (GRDC).

1.2.5 Soil moisture

Soil moisture is a critical variable for many practical applications because it influences net primary productivity, and agricultural production in particular. Surface soil moisture also controls the proportion of surface energy that is used in latent heating (evaporation) versus sensible heating. With climate change and a trend to warmer temperatures, soil moisture will tend to increase in those areas where increases in precipitation are larger than the increases in evapotranspiration.

Feedback from regions of high soil moisture to the atmosphere enhances local and regional moisture recycling. The extent to which soil moisture, and to a lesser extent vegetation, influences the formation of precipitation has been examined using model simulations. Model studies by Koster *et al*. (2004) have shown that soil moisture (or soil wetness) could have some memory, and could influence precipitation formation in areas such as the central USA, West Africa south of the Sahel, and northern India. In particular, moisture evaporated from saturated soils moistens the boundary layer, and this enables more clouds to form and more precipitation to be produced. Since the process occurs with a time delay, it is expected that the clouds and precipitation would be downwind from the original moist area; effects of soil moisture would then be largest over the central parts of large land areas. However, these soil moisture processes only promote precipitation when the soil is wet. When the soil is dry, they promote rainfall deficiencies – meteorological droughts – until external processes such as synoptic storms bring moisture into an area. Soil moisture has frequently been used for assessing climate model outputs, since soil moisture projections combine both precipitation and temperature effects. However, these projected changes are difficult to validate against real data because their spatial and interannual variabilities are very large, so the relatively sparse short-term observational networks in most areas cannot provide a baseline estimate of this variability. Furthermore, soil moisture measurements at a specific point do not necessarily correspond with the concept of an area-average soil moisture/soil wetness used in most models. New soil moisture measurement approaches, such as the European Space Agency's SMOS (Soil Moisture and Ocean Salinity) mission, will go a long way to remedying this deficiency in the observational network.

1.2.6 Groundwater

Groundwater aquifers provide large and important reservoirs of water in the global water system. The groundwater system consists of areas of recharge (where water enters the groundwater system from the surface) and other areas of discharge (where water leaves the groundwater system for the surface). Groundwater variations take place on time scales longer than variations in surface water systems. In areas with surface water shortages, aquifers are becoming a principal source of freshwater. Although we have measurements of relative changes in storage for a number of the world's aquifers, the total amount of groundwater in storage is basically unknown but is estimated to be roughly 20% of the water stored in the Earth's oceans. Reserves of groundwater are particularly important during extended droughts because they can continue to maintain wetlands and rivers and even deep-rooted trees after the shallow soil moisture reserves have dried out. Groundwater is being used increasingly in semi-arid areas to meet demands for domestic and irrigation water, leading to the 'mining' of older groundwater reserves (Rodell, 2005) in areas such as northern India and the western USA where groundwater has become the primary source of irrigation water. Future groundwater recharge will be increasingly sensitive to the decreases in recharge rates which come from warmer temperatures, increased evapotranspiration, and land use change.

1.2.7 Ice, glaciers and sea-level rise

A small but important component of the global water cycle involves land-based glaciers. These glaciers occur at high elevations in mountains or at high latitudes – areas where the amount of snow accumulation is greater than the amount that is melted during the summer months, with the excess snow slowly turning to ice. Since the formation of glaciers depends on temperature, it is expected that glaciers will be very sensitive to global change. In fact the mass balances for many glaciers in Europe have been negative, and the majority have been retreating since 1900. Some glaciers in the mountains of Central Asia have also been decreasing, as have those in North and South America. Although some of the findings have been contested, it is noteworthy that the recent IPCC report indicated that 80% of the mountain glaciers of the world are decreasing at present; the IPCC interprets this as a strong indicator that measurable climate change is occurring now (IPCC FAR, 2007).

Sea-level rise is another consequence of climate change that will have major implications for people and water resources in coastal areas. The expansion of the world's oceans due to rising ocean temperatures, along with increased runoff to the ocean from melting land glaciers, is expected to increase sea levels by 18–59 cm by 2100 (IPCC FAR, 2007). These amounts are significant because they will increase the risk of flooding in coastal areas and could aggravate coastal water management problems such as the salinisation of groundwater (which occurs when salt water penetrates sub-surface water systems in coastal areas).

1.2.8 Extremes

According to modelling studies reported in the FAR, climate change is likely to be accompanied by increases in the frequency of extreme events (primarily floods and droughts). For example, Kharin *et al*. (2007) suggested that the return period for heavy precipitation events may be reduced by a factor of about 2 (i.e. 20-year storms will become 10-year storms). This work suggests that many areas with intense rainfall will experience even more intense rainfalls in the future, while areas with dry conditions will experience even greater water stress (including longer-lasting dry periods).

The global water cycle functions as a fully integrated entity. Scientists must not only understand the changes in individual variables but also see how changes in one part of the system affect the behavior of the entire system. Trenberth *et al.* (2007) have reviewed the ERA-40 Reanalysis from the European Centre for Medium-Range Weather Forecasts (ECMWF) and identified a number of limitations in the estimates of water cycle variables produced by ECMWF. Some of the limitations come from adjustments made to bring the model into equilibrium when the global water and energy budget cannot be closed. Given these limitations in the representation of water cycle processes in these models, more research is needed to improve these models so that they can be confidently used to assess historical trends in the global water cycle. Through projects such as the Global Energy and Water Cycle Experiment (GEWEX) – which is continually improving data assimilation capabilities and the ability of models to utilise remote sensing data and to characterise the global water cycle on different time scales – progress is being made in the simulation and prediction of the water cycle.

The spatial variability of water availability is likely to be affected by the trends arising from climate change as well as changing land use patterns and modifications to the built system for water management. Although the total quantity of water being cycled through the global water cycle does not change much from year to year, regional changes can be very significant. The individual components of the global water cycle are relatively well monitored; a number (but not all) of the critical fluxes are being measured as Essential Climate Variables (ECVs) (GCOS, 2009) by the Global Climate Observations System (GCOS). It is clear that both observational and modelling systems need to be improved to properly define and characterise the changes associated with all aspects of global change.

1.3 Variations in the global water cycle

1.3.1 External forcing and its influence on the climate

The Sun, which powers the Earth's global climate system, provides a steady energy flux that has only relatively small periodic variations associated with its 11-year cycle. Recent modeling studies have shown that small variations associated with a solar maximum and minimum may affect the distribution of off-equatorial tropical precipitation maxima over the Pacific Ocean, lower eastern equatorial sea surface temperatures, and reduce the frequency of low-latitude clouds (Meehl *et al.*, 2009). Longer-term periodicities associated with the changing distance between the Earth and the Sun have been identified and described. More generally, the role of solar activity in forcing variability in the global water cycle is not well known and is in need of research.

Assessments of the long-term variability of the climate are often carried out using paleorecords derived from analysis of tree rings, lake sediments, ice cores, and other indicators of climate variability in the pre-instrument period. Although these records are restricted to locations where trees and sediments have been preserved for long periods, there is evidence that the Earth has been exposed to very dry periods and very wet periods lasting several decades. For example, based on tree-ring analysis, Sauchyn *et al.* (2003) and others have shown that multi-decadal dry periods have been common over the Canadian prairies during past centuries. Similar results have been found in the western USA and elsewhere. It is