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Excerpt
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# The realm of hydroclimatology

## 1.1 Water as a unifying concept

Water is an essential resource for humans and for natural ecosystems. Satellite images of the Earth show convincing evidence of an abundance of water on the planet. Unfortunately, only a small percentage of the total water volume is available as freshwater suitable for humans and many natural ecosystems. The relatively small volume of freshwater is further constrained by an uneven distribution over the globe that is paradoxical to the image of Earth as a water planet. Approximately one-third of the world's population lives in countries where the freshwater supply is less than the recommended per capita minimum, and 70 percent of all freshwater withdrawals from lakes, rivers, and groundwater is for crop irrigation to provide food (Entekhabi *et al.*, 1999). Such disparities in water supply and water demand require understanding the underlying physical processes that account for spatial and temporal differences in the occurrence and magnitude of the water supply.

The physical characteristics of water are significant in accounting for how the freshwater supply is sustained. A combination of natural processes collectively recognized as the hydrologic cycle provides the mechanism for the natural redistribution of water among the land, oceans, and atmosphere. Water is the only chemical compound that occurs in natural conditions as a solid, liquid, and gas. The transformation of water from one physical state, or phase, to another is a critical factor in the transportability of water. Water's phase changes and transportability in each of its phases are the foundations of the hydrologic cycle which constantly replenishes and redistributes the relatively small volume of freshwater.

Expanding knowledge of land–atmosphere interactions in the closing decades of the twentieth century heightened awareness of the strong coupling between climate and land surface hydrological processes embracing the hydrologic cycle. The long-term interest in the total hydrologic cycle shared by the disciplines of hydrology and climatology was magnified as the twenty-first century began with the emergence of non-traditional datasets and new investigative techniques applied to an expanding array of water-related problems. Accelerated interest in the hydrologic cycle was especially evident in the field of hydroclimatology that overarches the disciplines of hydrology and climatology.

### 1.1.1 *Hydrology*

Modern hydrology is broadly defined as the science that studies the occurrence and movement of water on and under the Earth's surface, water's chemical and physical properties, water's relationship to biotic and abiotic environmental components, and human effects on water (Ward and Robinson, 2000). Hydrology has a predominant land surface orientation and emphasizes processes involved in the land phase of the hydrologic cycle. Hydrology employs the sciences of biology, chemistry, ecology, mathematics, and physics to focus on solving water resource and water management problems concerned with water use, water control, and water quality. A watershed is often the most convenient spatial unit for integrative and synthesizing studies of hydrologic problems, but spatial scale variations are ultimately determined by the nature of the problem being examined.

### 1.1.2 *Climatology*

Climatology is an applied science that examines the fluxes of energy, mass, and momentum among the land and ocean surfaces and the atmosphere. These fluxes are integral parts of the climate system modulated by both external and internal factors (Peixoto, 1995). The vertical and horizontal fluxes of energy and mass that are central to climatology are components of physical and dynamical phenomena operating at various scales as an integrated and interactive spatial system that links the land and ocean surfaces with atmospheric circulation. Collectively these components embrace a broad spectrum of thermodynamic and hydrodynamic processes that display identifiable seasonal variations. The atmospheric general circulation is an expression of these seasonal variations, and the general circulation determines the concurrent array of weather patterns (Bryson, 1997). Therefore, the atmospheric phase of the hydrologic cycle is a climate-related phenomenon and one that is expected to display seasonal variability. Climatology requires knowledge of chemistry, mathematics, and physics and a thorough understanding of the atmosphere's physical and chemical interactions with the ocean and land surfaces. Climatologists apply this knowledge to understand atmospheric circulation and dynamics and the atmospheric role in climate variability and climate change. Modern climatology has a strong relationship with computers because simulation is an important aspect of climate science through its serving as the platform for climate experimentation (Petersen, 2000). Climate system models strive to reveal global energy and circulation conditions, flood and drought recurrence, the influence of land surface changes on climate, and climate's role in a variety of social, economic, and environmental problems.

### 1.1.3 *A broadened climate perspective*

The traditional concept of climate as the mean atmospheric condition expressed as average temperature, precipitation, and other weather variables and possibly higher moment statistics of these variables for a specified period (Peixoto, 1995), such as a month, a season, or a year, has a limited role in contemporary hydroclimatology. The climate variables are the same as those variables relevant to meteorology, but they are applied at different time and space scales. Climate expressed as the average weather or the average state of the atmosphere is almost synonymous with "statistical meteorology", and it is easy to see why meteorologists have some propriety about the province of climatology (Bryson, 1997). The movement of the atmosphere is the dynamic of interest behind the quantitative distributions used to depict climatic fields, but climate variables owe their importance to forecasting purposes in meteorology. Averaging is what makes the focus climatic. Individual weather events are explained by the incursion of air masses and fronts and by the vertical arrangement of the atmosphere. Consequently, averages and normals make climate appear statistical and useful as a descriptive tool. Probability estimates of extreme events are a logical ancillary feature of averages, and probabilities are widely used in construction and engineering professions.

A definition of climate exclusively concerned with the atmosphere ignores the coupling that exists between the atmosphere and the land and ocean surfaces. Therefore, the traditional view of climate as a static or constant entity does not fulfill the requirements of a contemporary construct of the climate system. The modern climate system (Fig. 1.1) is depicted as five subsystems linked by exchanges of energy, mass, and momentum among the subsystems. The coupling of the subsystems results in a dynamic climate undergoing constant change. This is a more accurate depiction of the actual natural processes involved in the continuous redistribution of energy, moisture, and momentum accomplished by the atmosphere's close interaction with the land, oceans, vegetation, and snow and ice at the Earth's surface. Climate is a direct response

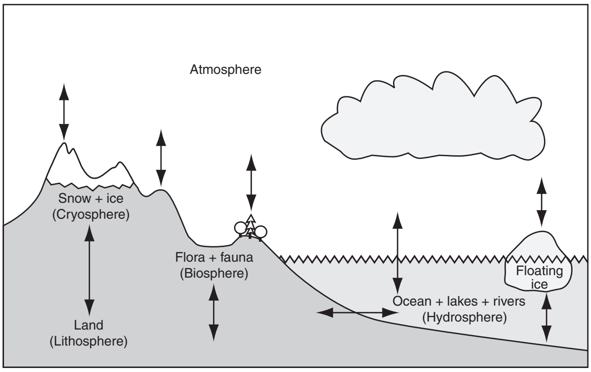


**Fig. 1.1.** The climate system. Arrows depict generalized fluxes of energy, mass, and momentum linking the five subsystems.

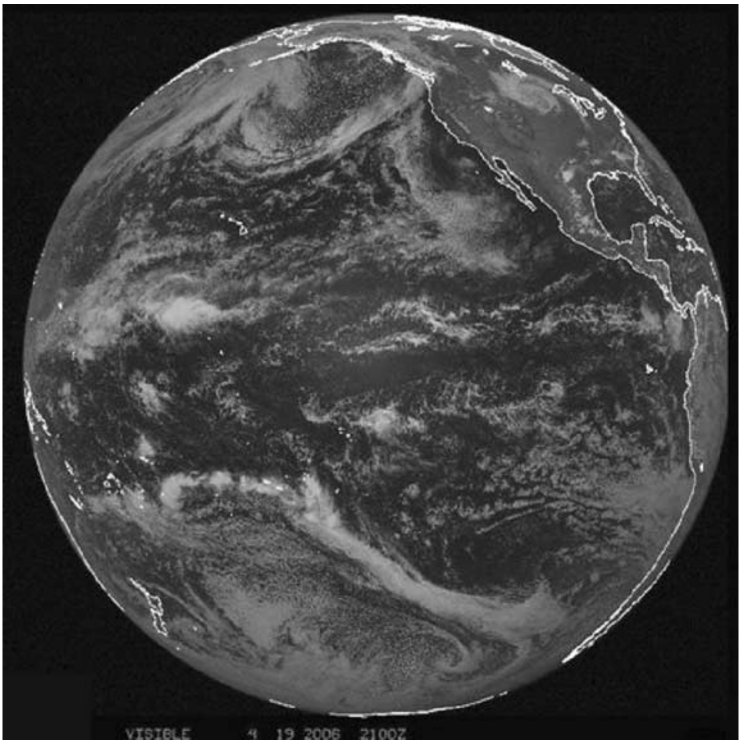


**Fig. 1.2.** GOES visible spectrum image of Earth on 19 April 2006. (Image courtesy of NOAA and the National Environmental Satellite, Data, and Information Service from their website at http://www.goes.noaa.gov/goesfull.html.)

to vertical and horizontal fluxes resulting from the coupling of the subsystems, and the atmosphere has an important transportation role. This dynamic climate perspective includes the more restrictive traditional concept of climate based on the mean atmospheric condition at the Earth's surface, but it emphasizes climate expressed as a physical system (Peixoto, 1995). Consequently, modern hydroclimatology is best viewed within the context of a thermodynamic and hydrodynamic system driving energy and moisture exchanges at the land and ocean surfaces while being influenced by these same energy and moisture fluxes. The resulting transport of energy and mass is evident in the structure and distribution of clouds revealed by satellite imagery (Fig. 1.2).

## 1.2 The global hydrologic cycle

The global hydrologic cycle is a logical unifying theme for hydroclimatology. For practical purposes, the global hydrologic cycle is a closed circulation for water's three phases. Within the structure of the general systems perspective commonly employed in the earth sciences, the hydrologic cycle is a subsystem and centerpiece of the global climate system. Consequently, the occurrence and movement of water assumes a primary role in both climatology and hydrology even though some illustrations of the hydrologic cycle lack comprehensive portrayal of the atmospheric transport role. Recognizing the full natural array of phenomena included in the hydrologic cycle is aided by conceptualizing the hydrologic cycle as consisting of two branches. The terrestrial branch encompasses continental processes and the atmospheric branch provides an energy and moisture redistribution mechanism (Fig. 1.3).

The terrestrial branch of the hydrologic cycle consists of the inflow, outflow, and storage of water in its various forms on and in the continents and in the

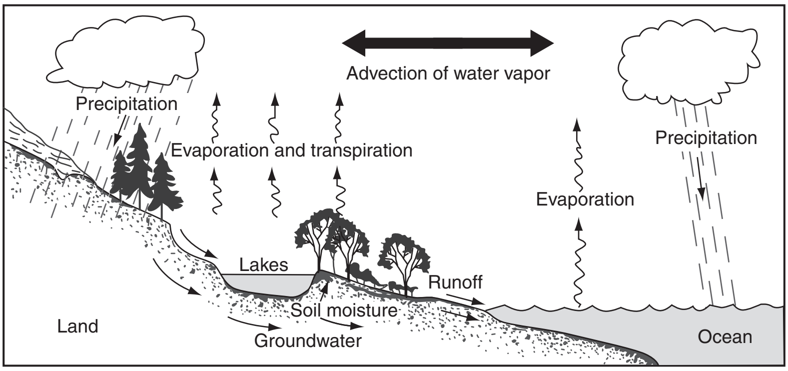


**Fig. 1.3.** The hydrologic cycle emphasizing both atmospheric and terrestrial branches.

oceans. The primary focus of the terrestrial branch is the natural processes at or near the land surface that ultimately produce surface and subsurface runoff and directly influence cycles of other materials that shape the Earth's surface (Stricker *et al.*, 1993). It is evident that the terrestrial branch is concerned with those processes commonly associated with hydrology.

The atmospheric branch of the hydrologic cycle consists of precipitation, evaporation, and the atmospheric transport of water mainly in the vapor phase. The two branches join at the interface between the atmosphere and the Earth's surface. The outflow of water from the Earth's surface through evaporation and transpiration is the inflow of water for the atmospheric branch. Precipitation, the atmospheric output, is a gain for the terrestrial branch of the hydrologic cycle. The atmosphere's mobility and ability to induce phase changes leading to precipitation establish the atmospheric branch as the forcing for the terrestrial branch of the hydrologic cycle. The dynamics of the hydrologic cycle are regulated by sources and sinks of atmospheric water vapor, by the thermodynamics of phase transitions, and by the dynamics of atmospheric general circulation (Peixoto, 1995).

The atmospheric branch of the hydrologic cycle is coupled with atmospheric general circulation and the transport of water vapor and the liquid and solid water in clouds. Recognizing the transport function of the hydrologic cycle is necessary to comprehensively portray how the hydrologic cycle is sustained. In addition to transporting moisture from the oceans to the continents, the atmosphere has an important role transporting energy vertically and horizontally as well as modulating the radiative forcing at the Earth's surface. The mobility of the atmosphere, and its capacity to force phase transitions of water establish the atmosphere as a forcing function for the terrestrial branch of the hydrologic cycle. The atmospheric branch of the hydrologic cycle is based on the dynamics of the general circulation of the atmosphere and is linked to the terrestrial branch by precipitation and evaporation (Peixoto, 1995). The role of vertical and horizontal transport of energy and mass and the delivery of precipitation places the atmospheric branch within the general framework of climatology and meteorology. However, the hydrologic cycle must be viewed as a whole and not in parts to comprehend its complete behavior and its complex non-linear feedback processes (Chahine, 1992).

## 1.3 Hydroclimatology defined

The American hydrologist Walter Langbein (1967) defined hydroclimatology as the study of the influence of climate upon the waters of the land. He identified precipitation and evapotranspiration and the imbalance of these climatic elements as the focus of hydroclimate. However, subsequent advances in understanding natural processes complemented by development of contemporary measurement techniques, data acquisition, and analytical tools suggest this perspective is too restrictive for modern science. Modern hydroclimatology requires a more holistic view that emphasizes a process orientation and a role in a variety of environmental systems ranging from water quantity and quality to stream habitats. Although the significance of the imbalance between precipitation and evapotranspiration remains valid, additional conceptual elements are needed to account for an expanding range of concerns.

The perspective adopted in this book is that hydroclimatology is an approach to studying moisture in its three phases in the atmosphere and on the Earth's surface. This realm is the intersection of climatology and hydrology, and it includes energy and moisture exchanges between the atmosphere and the Earth's surface and energy and moisture transport by the atmosphere. Emerging from this array of moisture fluxes and storages is a conceptual framework defining the occurrence of hydrologic events within their climatological context. The climatological context is a specific array or pattern of atmospheric pressure and circulation identifiable with a particular hydrologic event for a given location. For example, extreme events such as floods and drought tend to have well-defined atmospheric features related to the land surface event. This approach is consistent with the hydroclimatology perspective suggested by Kilmartin (1980) and Hirschboeck (1988). Such a robust concept of hydroclimatology includes hydrometeorology and knowledge of evaporation, runoff, interception, groundwater recharge and other surface or near-surface water relations (Mather, 1991). It does not attempt to define hydroclimatology as dealing with problems of the borderline between climatology and hydrology or the width of that borderline, which varies according to the view of the individual investigator. Perhaps most importantly, this approach to hydroclimatology does not attempt to set the breadth of the field but recognizes the opportunities for continual expansion with advances in understanding natural processes.

Hydroclimatology viewed as hydrologic events driven by climatically related energy and moisture fluxes and storages requires distinguishing between climatology and meteorology and hydroclimatology and hydrometeorology. Meteorology is the study of the weather or the day-to-day state of the atmosphere emphasizing variations in temperature, precipitation, pressure, wind, cloudiness, and humidity for a specific location. Meteorology employs physics and mathematics to explain short-term atmospheric motion and related phenomena. Hydrometeorology is the application of meteorology to problems involving the hydrologic cycle, the water balance, and the rainfall statistics of storms. In practice, hydrometeorology is concerned with measurement and analysis of precipitation data involving extrapolation of point data to spatial units, determination of rainfall probabilities, computing the frequency of intense storms, evaluating flood hazards, and design of local hydraulic structures. The boundaries of hydrometeorology are not distinct and the problems explored often overlap those of climatologists, hydrologists, cloud physicists, and weather forecasters.

One of the strengths of the hydroclimate concept is that it is robust. It is applicable to the study of a broad range of natural processes. It is equally useful for examining human modification of the climate system or the hydrologic cycle. Hydroclimate emphasizes study of the precipitation–evapotranspiration difference and the consequences of the imbalance. Precipitation and evapotranspiration are due to different meteorological, physical, and biological causes. For any given location they are not often the same in either amount or distribution through the year. The character of this imbalance is the basis for defining the hydroclimatic significance of an event or set of conditions. Hydroclimatic significance provides the structure for examining a series of important questions. What is the nature of the imbalance? What accounts for the imbalance? What are the ramifications of the imbalance in terms of how water is processed at the land–atmosphere interface?

## 1.4 Emergence of the hydrologic cycle

An early record of the importance of water for human life can be found in Genesis, the first book of the Bible. In this account of creation, light is provided on day one by the Sun, Moon, and stars. Separation of waters below the sky from waters above it occurs on day two, and day three begins with the separation of land and oceans.

Contemporary thought recognizes that energy from the Sun warms the Earth and water dominates the distribution of heat over the planet (Langenberg, 2002), and the related energy and moisture transfers constitute the global hydrologic cycle. Consequently, the light and water present at the beginning of time represent the ingredients needed for the hydrologic cycle.

The full context of contemporary hydroclimatology emerges from the historical pursuit of knowledge to understand the Earth's atmosphere and the hydrologic cycle. The early work was motivated by individual interests and curiosity, but over time the accumulation of information formed a coherent body of knowledge. False starts and imprecise ideas often related to mythology occurred, but these were identified and corrected or abandoned. An overview of the development of climatology and hydrology indicates the similarities and differences in how these two fields developed, the role of the hydrologic cycle in their development, and the ultimate emergence of hydroclimatology out of the two disciplines.

### 1.4.1 *Speculation period*

The rise of climatology as a science is closely related to developments in meteorology and to the human capacity to obtain more and improved atmospheric observations and measurements. The earliest evidence of human interest in the atmosphere was a concern for phenomena recognized in today's world as belonging to the field of meteorology. Climate is a more abstract concept than weather, and in these early days people did not travel extensively and were less likely to observe climatic differences between places (Linacre, 1992). However, interest in climate evolved as understanding of atmospheric processes improved, and a close coupling of climatology and meteorology characterizes much of their early history. Around 3000 BC, Mesopotamian astronomers and mathematicians studied clouds and thunder and were the first to identify winds according to the direction from which they blow. At about this same time, Egyptian astronomers and mathematicians recognized that the seasonal position of the Sun in the sky is a basic factor underlying climate differences. Climate was mentioned in the writings of the Xia dynasty in China (2100–1600 BC), and weather details were recorded in China as early as 1500 BC.

The earliest written record recognizing the global hydrologic cycle is attributed to the author of the book of Ecclesiastes around 1000 BC (Nace, 1974). Pre-800 BC texts in India may be the earliest indication of human understanding of the atmospheric branch of the hydrologic cycle (Ward and Robinson, 2000). However, the human necessity for water required numerous responses that predate writings about the hydrologic cycle. As early as 3000 BC, occupants of the Indus Valley in India constructed water supply, irrigation, and drainage systems, and Egyptians constructed a rock-fill dam between 2950 and 2750 BC. A variety of water facilities were constructed in Assyria, Babylonia, Israel, Greece, Rome, and China before the Christian era.

### 1.4.2 *Greek and Roman era*

Early Greek philosophers were interested in weather phenomena, the atmosphere, and the hydrologic cycle. Herodotus (440 BC) compared the climate of places, and Hippocrates in 400 BC wrote about weather and health and the dangers of drinking polluted water. Aristotle wrote a comprehensive meteorological treatise in 334 BC that served as the basis for weather theory for the next 2000 years. Erastosthenes described climate in terms of the Sun's position in the sky in 200 BC. In general, early Greek philosophers embraced the basic idea of the hydrologic cycle and proposed a variety of explanations for the origins of rivers and springs. Some proposals portrayed reasonable constructs, but underground mechanisms were imaginary.

The sustained influence of Aristotle's meteorological treatise was partially due to Roman philosophers devoting little interest in the atmosphere. Roman philosophers were more concerned with hydrology and benefited from practical knowledge gained from construction of great hydraulic works. They expanded on the explanations of rivers and springs proposed by the Greeks, and Vitruvius, a Roman architect and engineer, in 100 BC conceived that groundwater is derived from rain and snow infiltrating from the surface. Many consider this theory to be the forerunner of modern hydrologic cycle concepts. Although Ptolemy (AD 130), a Greek astronomer living in Alexandria, created a map that divided the known world of the second century into seven roughly determined climatic zones, Roman philosophers, at the fall of the Roman Empire in AD 476, had contributed little toward understanding the atmosphere.

### 1.4.3 *Middle Ages*

With a few exceptions, advances in understanding the atmosphere and the hydrologic cycle by Western scholars languished between AD 400 and 1500 during the period known as the Middle Ages. The attention these topics received during this period came largely from other world regions. In the late tenth century, the Persian scholar Karaji described the basic principles of hydrology (Pazwash and Mavrigian, 1981). Norse poems of the ninth to twelfth centuries contained descriptions of the hydrologic cycle indicating recognition of the roles of ocean evaporation, condensation, cloud formation, and precipitation on the land (Ward and Robinson, 2000). Except for the introduction of the wind vane in AD 850, few advances in understanding the atmosphere were achieved, but Islamic scholars during the ninth to twelfth centuries translated and expanded on the work of the Greeks and Romans. By the middle of the fifteenth century, extended sea voyages opened new trading areas and the broadened knowledge of ocean winds acquired as a result of these voyages contributed to formulation of theories regarding global wind patterns.

### 1.4.4 *Observation period*

Early Greek and Roman theories of the hydrologic cycle remained dominant until the sixteenth century when Leonardo da Vinci in Italy and Palissy in France used field measurements to assert that the water in rivers comes from precipitation (Biswas, 1970). The observation-based approach to the hydrologic cycle was advanced in the late seventeenth century when Perrault and Mariotte in France and Halley in England provided a quantitative basis for the basic principles of the hydrologic cycle by showing that precipitation supplied the water in rivers and streams and moisture circulated between the land, oceans, and atmosphere. Measurements enabled scientists to draw