Chapter

Hydrometeorology: Review of Past, Present and Future Observation Methods

Mohammad Valipour, Sayed M. Bateni, Nicolas R. Dalezios, Mansour Almazroui, Essam Heggy, Zekai Şen and Andreas N. Angelakis

Abstract

Hydrometeorology aims at measuring and understanding the physics, chemistry, energy and water fluxes of the atmosphere, and their coupling with the earth surface environmental parameters. Accurate hydrometeorological records and observations with different timelines are crucial to assess climate evolution and weather forecast. Historical records suggest that the first hydrometeorological observations date back to *ca* 3500 BC. Reviewing these observations in the light of our modern knowledge of the dynamic of atmospheres is critical as it can reduce the ambiguities associated to understanding major fluctuations or evolutions in the earth climate. Today, the ambiguities in hydrometeorological observations have significantly improved due to the advances in monitoring, modeling, and forecasting of processes related to the land-atmosphere coupling and forcing. Numerical models have been developed to forecast hydrometeorological phenomena in short-, medium- and long-term horizons, ranging from hourly to annual timescales. We provide herein a synthetic review of advances in hydrometeorological observations from their infancy to today. In particular, we discuss the role of hydrometeorological records, observations, and modeling in assessing the amplitude and time-scale for climate change and global warming.

Keywords: hydrometeorology, sustainability, weather monitoring tools, climate, forecasting, innovations

1. Introduction

In general, hydrometeorology deals with monitoring the energy and water fluxes between the atmosphere and earth [1–4]. Hydrometeorology has evolved as a special discipline of both meteorology and hydrology, linking the fundamental knowledge of meteorologists with the needs of hydrologists to assess the water and energy cycles at local, regional, and global scales [1–4]. In hydrometeorology, meteorological data are incorporated into hydrological models to predict water and energy exchanges between the land surface and atmosphere, weather, climate, and natural hazards such as wildland fires, storms, droughts, and floods [5–8]. Climatologists focus on seasonal to decadal scales, while hydrometeorologists are more interested in studying short time-scale events (i.e., hours up to a few days) such as severe storms and flash floods [6, 8].

Hydrometeorological records started in *ca* 3000 BC mainly by observing the movement of moon and stars. Since then, our understanding of hydrometeorology has advanced considerably, especially with the significant growth of technology in the second half of the 20th century (e.g., introduction of televisions in the early 1950s and computers in the 1970s).

From the 1980s up to now, tremendous advances have been made in the hydrometeorological science [9]. Governmental and private agencies have begun hiring hydrologists to use meteorological data and improve the accuracy of hydrometeorological predictions. A better knowledge of hydrometeorology along with the enhanced computational capabilities allowed them to forecast hydrometeorological variables more accurately. Fortunately, TV networks and websites have provided timely information on the weather and climate forecast.

With the advent of satellites and radars, hydrometeorology has changed from a "data poor" to a "data rich" environment [10]. Nowadays, hydrometeorologists incorporate remotely sensed data from radars and satellites into numerical models to estimate hydrologic variables such as rainfall, evapotranspiration, soil moisture, and vegetation dynamics over large-scale domains. Indeed, the technology boom and the vast amount of radar and satellite observations have enabled many national hydrometeorological centers to become hubs of information and research in the field of weather forecasting for governments, policymakers, and private agencies. The improvements over the last 50 years have been impressive, and hydrometeorological centers are continuously adopting modern technologies to provide more reliable weather and climate information for societal needs [1–4].

Five eras can be identified as the benchmark for historical advances in the science of hydrometeorology: (1) Prehistoric times (*ca* 3500–750 BC), (2) Historical to medieval times (*ca* 750 BC-1400 AD), (3) Early and mid-modern times (*ca* 1400–1800), (4) Modern times (1800–1900), and (5) Contemporary times (1900-present).

This study provides new information and insights about history of hydrometeorology. A comprehensive review of hydrometeorology in each of the abovementioned five eras contributes to a growing awareness of observational methods. As noted by the great Chinese philosopher, Confucius (*ca* 551–479 BC): *Study the past, if you would divine the future*.

2. Hydrometeorology in prehistoric times (*ca* 3500–650 BC)

In the prehistoric period, also known as the speculation period, the meteorological knowledge was based solely on speculative theories [9]. In this long era, hypotheses with no empirical validation were developed to describe meteorology, weather, and climate [9]. The prehistoric times cover the pre-Aristotelian era that is long before the invention of meteorological instruments.

The first primitive human societies began in the late Neolithic era [9]. The transition from hunting-gathering to farming increased the vulnerability of societies to climate-related hazards because they no longer migrated to avoid unfavorable environmental conditions. There was no study of meteorology at that time. Also, atmospheric phenomena could not be adequately explained. Hence, a collection of linguistic weather "signs" was created and transferred from generation to generation. For instance, moving a light or star at night was considered as a sign for sunny or rainy condition in the next day.

Figure 1.
The Nilometer at Rhoda Island in Cairo.

About 3000 BC, an ancient instrument (called a Nilometer) was first used to measure the water level of the Nile River. The Nilometer helped farmers irrigate their farms more efficiency [11]. **Figure 1** shows the Nilometer at Rhoda Island in Cairo (in 861 AD), which was designed by Afraganus.

The Babylonian king Hammurabi (*ca* 1792–1750 BC) related seasons and weather conditions to the solar cycle by developing the 360-day calendar. This calendar was used to study hydrometeorological phenomena in next centuries [11].

From 747 BC to 737 BC, other Babylonian kings (e.g., Nabu-nasir) recorded the movement and location of the moon over a period of several years. He also monitored the time of sunrises, sunsets, and eclipses. The Babylonians used this information to predict celestial events [12]. Another Babylonian king, named Nabu-suma-iskun (*ca* 700 BC), stated that a halo around the sun or the moon is a sign of flood during winter [13].

3. Hydrometeorology in the archaic to medieval times (*ca* 650 BC–1400 AD)

The theocratic explanation of meteorology was dominant until the 7th century BC. The Ionian Stoa (School) in Asia Minor was founded *ca* 600 BC by the Thales of Miletus, the father of natural philosophy and water science. The natural philosophers (the so-called pro-Socratic philosophers) such as Thales, Anaximander, Anaximenes, Pythagoras, Heraclitus, Zenos, Empedocles, Democritus, and Alcmaeans lived in Greece from the end of the 7th century until the middle of the 5th century BC. They raised new questions about the natural phenomena such as rain, cloud, storm, and lightning [14]. One of their questions was: "Is there a reality that does not change despite the ever-changing appearances of things?" [14]. While the manifestations of nature are extremely complex, the beginning (i.e., the source substance) was thought to be relatively simple. Having said that, the "beginning" was water for Thales and the air for Anaximenes [14].

In the late Archaic times, the Ionian philosophers learned fundamental hydrological processes by studying meteorological phenomena [14]. For example, Anaximander (*ca* 610–546 BC) explained the relationship between rainfall and sunshine in his book entitled "*On Nature*". For the first time, Xenophanes (*ca* 570–475 BC) expressed the concept of the hydrological cycle and the role of sea in it.

In 465 BC, Anaxagoras (*ca* 500–428 BC) used the ideas of the Ionian philosophers to develop rain gauge instruments in Athens [15]. At that time, the first measurements of rainfall began in India [16, 17]. Later, in 100 AD, a recording rain gauge was developed in Palestine [18]. In 400 BC, Kautilya wrote a book entitled *Arthashastra*in, which elaborated the importance of rainfall for military operations [16, 17].

Plato, a well-known philosopher, advanced the concept of the hydrologic cycle by stating that "rivers and springs originate from rainfall". In 387 BC, the Platonic Academy was founded in Athens by Plato (*ca* 428–348 BC) based on the principles of the Ionian Stoa. The hydrological cycle was characterized in that Academy. Aristotle (384–322 BC) was Plato's student, and his theories were influenced by Ionian philosophers. He explained several hydrometeorological phenomena such as physics of clouds, rivers, precipitations, and changes in land covers [19–24].

In 300 BC, Theophrastus (*ca* 371–287 BC) published his Book on Signs (*De Signis Tempestatum*), which is considered to be the first weather forecasting manual. In 240 BC, Eratosthenes compared the intensity of Sun's rays at two points on the earth to calculate the spherical size of the earth and its circumference [25].

The well-known astronomer, Ptolemy (*ca* 100–170 AD), defined the earth's climatic zones on the basis of astronomical observations and air temperature variability. Recognition should also be given to two Roman scholars, Seneca (4 BC-65 AD) and Pliny (23/24–79 AD). Seneca studied a wide spectrum of meteorological phenomena (e.g., wind, lightning, thunderstorm and hurricane). Pliny collected all the meteorological theories of the Ancient Greeks [26].

Heron of Alexandria (*ca* 10–75 AD) was a physicist, mathematician, and engineer at the Museum of Alexandria. He wrote many books in his field of expertise that were used until medieval times. His most important invention was the Aeolipile, the first steam turbine [27]. He is mostly known for his profound comprehension of physics, which is reflected in the Pneumatica (his description of how mechanical devices operate by air, water, and steam) [28].

Documents from the Jewish tradition (called the Mishnah) show the rain water harvesting practice from *ca* 200 BC to 200 AD. During the Han dynasty (*ca* 206 BC-220 AD) in China, the hydrological cycle was represented by the 1) water vapor transfer from the land surface to the overlying atmosphere due to evaporation, and 2) cloud formation.

In 800 AD, Vikings in Scandinavia believed in Thor as the god of thunders and lightning, and Freyr as the god of sun, rain, and other meteorological phenomena. Thunder was the sound of Thor, and lightning was the sign of killing Thor's enemies [29].

In *ca* 1000 AD, Ibn Wahshiyya discussed the importance of weather forecasting for agricultural production in his book entitled "*Nabataean Agriculture*". According to Wahshiyya, a visible moon is a sign of clear weather in the next day. Unlike the ancient Babylonians, he believed that clear weather would come if the moon was surrounded by a halo. Wahshiyya also mentioned that thin (thick) clouds were the sign of cold (warm) weather. Based on his beliefs, an owl's hoot implies the closeness of cold weather [30].

In 1328 AD, William of Ockham (1285–1347 AD) wrote a great deal on natural philosophy and attempted to quantify atmospheric physics and other natural sciences. William highlighted the importance of reliable meteorological observations in a long commentary on Aristotle's Physics [31–33].

4. Hydrometeorology in early and mid-modern times (*ca* 1400–1800)

During this era, many scientists tried to develop new methods and instruments to monitor hydrometeorological variables. The end of the era of theories and the beginning of the modern meteorology are demarcated by the first 'modern philosopher', Rene Descartes (1596–1650 AD). He established the principle of scientific philosophy in his work *Les Meteors,* denoting nothing should be accepted as truth unless it is proven [34].

The economy of Korea in the Far East during the Joseon Dynasty (1392–1897) was mainly dependent on agriculture. Thus, Koreans had to manage their water resources efficiently. Jang Yeong-sil designed the first Korean rain gauge (called *cheugugi*) in 1441 (**Figure 2**). In 1442, the standard rain gauges with the height of 42.5 cm and diameter of 17 cm were installed across Korea to record rainfall data [9].

As the Renaissance began, weather forecasts were based on astrology and interpretation of weather signs. Meteorological instruments were improved only slightly from the middle ages until the beginning of age of instrumentation in the 17th century. In 1450, Nicholas of Cusa developed an idea for a hygroscopic hygrometer to measure air moisture. His plan was to use wool and stones on different sides of a large scale. The hygrometer operated based on the ability of wool fibers to absorb air moisture. In 1481, Leonardo DaVinci took advantage of Nicholas' idea and made the first hygrometer (**Figure 3a**). DaVinci's invention was used until 1500 [9]. Later, Francesco Folli (1624–1685) created a hygrometer (**Figure 3b**), which he named as *"Mostra Umidaria"* (in Italian). In his hygrometer, a frame carries a small roll at each end, on which is wrapped the end of a paper ribbon (now missing) serving as a hygroscopic substance. The frame is made of brass and has the shape of a finely decorated balustrade. The center of the frame holds a decorated brass dial fitted with a circular graduated scale. By means of a simple mechanical system, the dial indicates the changes in ribbon length due to the variations in atmospheric humidity [37]. Nevertheless, the development of hygrometer as a scientific instrument was started in 1768 by the German mathematician John Heinrich Lambert (*ca* 1728–1777).

The British physicist, Robert Boyle (1627–1691), was one of the first scientists that recognized the need for a standard thermometric scale to make temperature measurements comparable. In 1714, Gabriel Daniel Fahrenheit (1686–1736) built a mercury thermometer that could measure the temperature as low (high) as the freezing (boiling) point of water. Anders Celsius (1701–1744) proposed a new scale for thermometers in 1742. His 'centesimal' (meaning 100 divisions) system was easier to use in scientific works and became the basis for the 'Celsius' or 'centigrade' temperature scale. In 1862, Lord Kelvin (1824–1907), the Scottish mathematician and physicist, used the absolute zero (or zero degree Kelvin) in the so-called absolute temperature scale. Absolute zero is defined as the temperature in which molecules stop moving [38]. Benedetto Castelli (1578–1643) built the first rain gauge in the 16th century in Italy. More meteorological instruments were developed by other Italian meteorologists. Ferdinand II de' Medici (1610–1670) built a condensation hygrometer that operated by exposing water vapor to a cylindrical iced glass.

The science of hydrometeorology has benefited from advances in mathematics and physics. The relationship between air pressure and height was one of the most interesting subjects in the history of hydrometeorology. Evangelista Torricelli and Blaise Pascal developed the first barometers in 1643 and 1646, respectively. In 1660, Robert Boyle found the relationship between the gas pressure and volume. Benjamin Franklin (1706–1790), the American statesman and scientist, discovered the electrical nature of lightning in 1752. He also realized that storms can move from

Figure 2.
The first Korean rain gauge designed by Jang Yeong-sil [9].

a b

Figure 3.
(a) The DaVinci's hygrometer [35, 36], and (b) the Francesco Folli's hygrometer, named as Mostra Umidaria [37].

place to place. In 18th century, the first studies on dynamic meteorology were done by Halley and D'Alambert [39].

The equations of motion, the continuity equation, the first law of thermodynamics, the state equation of gases (the law of ideal gases), and the hydrostatic equation have been used to describe atmospheric motions [9]. The first law of thermodynamics was formulated in the 19th century by Germain Hess and Rudolf Clausius. Isaac

Newton (1642–1727) introduced many principles of mechanics in an integrated framework and highlighted their use in describing atmospheric phenomena [40]. Leonard Euler (1707–1783) investigated the variation of air pressure with height above sea level. Using the Newton's second law of motion, he developed the equations of fluid flow in 1755, which were a significant contribution to fluid mechanics [40].

The development of hydrometeorology was further enhanced in the late 17th and early 18th century. Robert Hooke (1635–1703 AD) had new ideas for designing hydrometeorological instruments. His collaboration with Sir Christopher Wren led to the construction of the first automatic rain gauge, called the tipping bucket rain gauge [27, 33]. Richard Towneley (1677–1704 AD) used their automatic rain gauge to measure rainfall in the UK [27, 33].

In the 18th century, scientists improved the accuracy of instruments to monitor meteorological phenomena more reliably. In 1743, Benjamin Franklin studied the movement of hurricanes in Philadelphia and Boston. Horace-Benedict de Saussure (1740–1799 AD) improved the accuracy of hygrometers by designing a hair hygrometer in 1775, which is still used today [41, 42]. de Saussure's hair hygrometer works based on changes in the length of a human hair as air humidity varies. In the late 1700s, hydrometeorologists started to monitor meteorological variables over large-scale areas. For instance, in 1777, David Dobson measured raindrop size and evaporation over Liverpool in the UK ([29, 43]). In summary, the 18th century was characterized by the development of basic meteorological instruments and dynamic equations [44]. However, the widespread application of these tools and equations began in the 19th century.

5. Hydrometeorology in modern times (1800–1900)

In the 19th century, meteorological scientists used new devices (e.g., psychrometers, hygrometers, meteorographs, and weather kites) in weather stations. They also categorized several meteorological phenomena such as clouds, hurricanes, and tornadoes. The English naturalist Luke Howard (1772–1864) classified different types of clouds in 1803. In 1830, the Connecticut merchant William Redfield (1789–1857) discovered the circular motion of hurricanes. He also classified different types of hurricanes and tornadoes [44, 45].

The British Admiral Francis Beaufort (1774–1857) developed a wind force scale for mariners in 1806. Ernst Ferdinand August (1795–1870) built a psychrometer to measure air humidity in 1818. It used a dry bulb thermometer and a wet bulb thermometer to measure air temperature [9]. The difference in temperature of the two thermometers was utilized in the Ernst Ferdinand August's algorithm to obtain air humidity. In 1820, John Frederic Daniell (1790–1845) invented a new type of hygrometer, called a dew point hygrometer [46]. He cooled down a polished metal mirror to a temperature at which water vapor in the air began to condense on it (i.e., dew point temperature). William Jevons (1835–1882) corrected the errors of rain gauge measurements due the wind. George James Symons (1838–1900) expanded Jevons' corrections and founded the British Rainfall Organization (British [47, 48]).

The first synoptic weather charts were constructed by the German meteorologist Heinrich Wilhelm Brandes (1777–1834) in 1820. These weather charts were a significant milestone in the history of theoretical and applied meteorology. These weather charts indicated the low- and high-pressure systems and initialized the field of synoptic meteorology [49, 50].

By the invention of telegraph in 1843, the first weather observation network was established in the UK to transmit weather observations to various stakeholders. In 1860, the Met Office in London started to transmit meteorological measurements to the community by telegraph. The British Meteorological Society (BMS) was created in 1850 and later renamed to the Royal Meteorological Society (RMS). In 1861, the Met Office began publishing weather forecasts for the public in the UK [51, 52].

The first attempt to automatically record meteorological variables was made by Father Secchi in 1867. He designed the first Meteorograph to measure air pressure and rainfall duration (**Figure 4a**). In 1870, weather balloons were employed by Alexander Wilson in the UK to collect meteorological data [9]. In the late 1880s, meteorological stations were installed in other countries. For example, the civic association Stadtverein Salzburg installed a weather station in Salzburg (Austria) in 1888 to measure air pressure, temperature, and humidity (**Figure 4b**) (Atlas [54]).

In 1870, President Ulysses S. Grant established a weather bureau in the US, currently called the National Weather Service (NWS) [55]. By the 1870s, the US had more than 20 weather stations that transmitted micrometeorological data to Washington DC by telegraph.

The International Meteorological Organization (IMO) was founded in 1873 to facilitate the cooperation among all national weather services. The IMO organized several international meteorological conferences in Vienna, Rome, Munich, and Paris in 1873, 1879, 1891, and 1896, respectively. The IMO was renamed to the World Meteorological Organization (WMO) in 1950. Nowadays, the WMO serves as the specialized agency of the United Nations for meteorology (weather and climate), agrometeorology, operational hydrology, and related geophysical sciences [9]. Currently, the

a **b**

Figure 4.
(a) The Meteorograph designed by father Secchi [53], and (b) the first (19th century) weather station in Salzburg, Austria.

Figure 5.
Measuring weather information by a weather kite in 1894. The location of the picture is unknown [9].

WMO has at least 187 member states and territories. The Japan Meteorological Agency (JMA) and the Meteorological Society of Japan were formed in the 1880s [9].

In the late 1890s, further attempts were made to measure various micrometeorological variables. Weather kites were used in 1894 to collect air temperature, pressure, humidity, and wind speed at high altitudes (**Figure 5**) [9]. Weather kites were used instead of weather balloons (developed in late 1780s) as they could move more readily. In 1898, the Richard brothers in France invented a barothermograph, which consisted of a thermometer, a barometer, and a hygrometer [56].

6. Hydrometeorology in contemporary times (1900–present)

The modern hydrometeorology was born in contemporary times (1900-present). In this era, weather data were used in the forecast models [9].

The discovery of the stratosphere at the beginning of the 20th century by Léon Philippe Teisserenc de Bort (1855–1913) advanced meteorology and hydrometeorology. Similarly, the discovery of the tropopause (i.e., the buffer zone between troposphere and stratosphere) by Ernest Gold (1881–1976) and William Jackson Humphreys (1862–1949) in 1900 further augmented hydrometeorology. In 1920, the Norwegian School of Meteorology (NSM) made a significant contribution to the field of meteorology by organizing seminars and inviting the most well-known scientists to them [57]. New theories about frontal surfaces and development of low-pressure systems by the Norwegian scientists, namely Vilhelm Bjerknes (1862–1951), Jacob Aall Bonnevie Bjerknes (1897–1975), Halvor Solberg (1895–1974), and Tor Bergeron (1891–1977) took a dominant position in hydrometeorology [58]. In 1940, Carl Gustaf Rossby (1898–1957) from the US weather service discovered the jet stream and its controls over the easterly movement of most weather systems [59].

Hugo Hildebrand Hildebrandsson (1838–1925) published his book entitled *International Cloud Atlas.* His book improved meteorologists' knowledge of cloud physics [60, 61]. In 1909, the Met Office equipped ships with wireless telegraphy to transmit weather records to designated centers in the UK. This was the first attempt to transfer real-time weather data from the ships to the land [62]. The American Meteorological Society, AMS (founded in 1919), has advanced our understanding of meteorology, hydrometeorology, and hydroclimatology. In 1922, Lewis Fry Richardson used weather observations in his simple numerical model to forecast air pressure and wind speed. Today, complex numerical models are used instead of his simple weather forecast algorithms [9, 63].

In 1922, the first weather radio broadcasts were developed in New York and London [64]. In 1921, the Hydrometeorological Center of Russia was founded in Moscow. Nowadays, this center has more than 30 laboratories, departments and administrative branches, and provides forecasts of hydrometeorological variables. The US broadcasted the first weather forecast program on television in 1941 [64].

The prestigious seminars of Norwegian School of Meteorology, the invention of radiosondes, the Bergeron's theory of rain formation, the ionospheric research of Edward Victor Appleton (1892–1965) and Miles Aylmer Fulton Barnett (1901–1979), and the theoretical studies of low- and high-pressure systems were conducted between the First and Second World Wars (1920–1940). In addition, in this period, there were some studies on the general circulation of atmosphere, the properties of motion, the mechanisms of fronts and low-pressure systems, the atmospheric disturbances, and the isentropic analysis [58]. During the Second World War, radiosonde meteorological measurements led to the discovery of jet stream. In 1935–1945, new instruments such as weather radars and radio wave sensors were invented [58]. In the same period, several studies were performed on the chemical composition of the upper atmosphere and fog decomposition [58].

Jule Charney used the first computer in 1950, called the Electronic Numerical Integrator and Computer (ENIAC), to run his meteorological model [9]. In the 1950s, the first computational atmospheric models were developed and used in hydrometeorology. In this decade, government agencies took advantage of geographical information to forecast weather more accurately. In 1954, the first radar weather station was built in New Orleans, USA [9]. In 1959, the Met Office created a computer, called Meteor, which was able to conduct 30,000 calculations per second [65].

The chaotic nature of the atmosphere was first realized by Edward Norton Lorenz (1917–2008) in the 1960s. He introduced the chaos theory and limitations of atmospheric predictability. This is also known as the butterfly effect as flapping of a butterfly's wings can cause a large disturbance somewhere else [58]. The first generation of satellites emerged in this decade. In 1960, the first weather satellite, called the Thermal Infrared Observation Satellite (TIROS), was launched by the US. This satellite could send 4000 images per week to the earth [66].

The National Aeronautics and Space Administration (NASA) lunched the Synchronous Meteorological Satellite-1 (SMS-1) and SMS-2 in the 1970s. Other geosynchronous meteorological satellites were also launched by the NASA as part of the Geostationary Operational Environmental Satellite (GOES) program.

There is a large number of satellites at present, which is steadily increasing year by year for remote sensing of the earth. Remote sensing can be classified into two main categories: (1) active radars, and (2) passive instruments (sensors). The active radars transmit energy and record the backscattered signals. Weather radars can operate even in cloudy skies because their signals can pass through clouds. The passive systems record the emitted radiation from the earth.

Scientific and technological advances led to the development of Doppler and dual-polarization weather radars, which are currently used to detect storms [44]. These radars allow researchers to "see" inside the storms and monitor wind-driven precipitation. They also visualize the wind rotation and allow meteorologists to detect severe storms such as tornadoes and mesoscale convective systems.

Meteorological satellites are located in either low polar (e.g., Polar Orbiting Environmental Satellites (POES) and Television Infrared Observation Satellites (TIROS-N)) or high geostationary (e.g., meteorological satellites (METEOSAT) and GOES satellites) orbits. A number of widely used meteorological satellites are shown in **Figure 6**. They monitor the weather, soil moisture, sea and land surface temperatures, precipitation, crop condition, snow depth, land cover, landslide, etc. [16]. While these satellites allow to monitor various hydrologic variables, they have main challenges regarding community acceptability, underestimating total precipitation due to light rainfall events, unquantified uncertainty, data continuity, sensor changes, and data maintenance [67, 68].

Continuity of data is crucial in order to develop reliable and accurate satellite records for hydrologic applications. Most satellites are functional for less than 10 years, though many of them operate beyond a decade. Although, launching satellites should be extended for follow-up missions, designing satellites require substantial investments and can take decades. The Global Precipitation Measurement (GPM) and Gravity Recovery and Climate Experiment (GRACE) are two examples of satellite missions planned to fix the problem of the gaps in the current satellite-based precipitation and total water storage data, respectively [67, 68]. Nowadays, the quality and resolution of satellite images are significantly improved [69, 70]. **Figure 7** shows the image of the Gulf of St. Lawrence from the TIROS-1 weather satellite (1970s) and Suomi National Polar-orbiting Partnership (S-NPP) satellite. As can be seen, there is a remarkable improvement in the quality and resolution of the image from 1970s up to 2013. The improvement in satellites has helped understand hydrological phenomena such as glacial lake outburst flood [71] and soil erosion [72], which were difficult to study in the past [71].

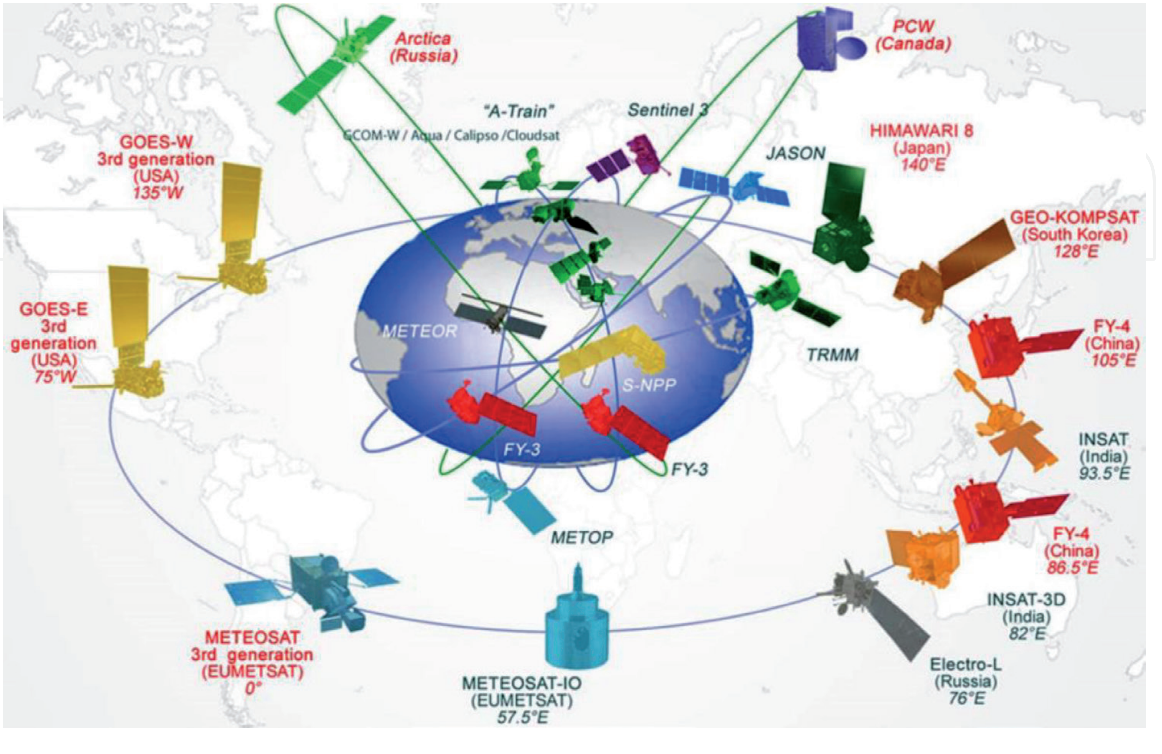

Figure 6.
A number of widely used satellites that monitor and transit meteorological and climatological information [9].

Today, new technologies such as microwave sensors (**Figure 8a**) and drones (**Figure 8b**) allow to monitor extreme events (e.g., floods, droughts, and hurricanes) and mitigate their damage on the environment, infrastructures, and critical resources [9].

Weather models were developed at the end of 20th century and beginning of 21st century. The first real-time medium-range forecasting model was developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) in 1979. The Intergovernmental Panel on Climate Change (IPCC) was founded in 1988 by the United Nation (UN) to monitor climate change, and its economic, social and environmental impacts across the world. In the 1990s, the Weather Research and Forecasting (WRF) model was developed by simulating the atmospheric processes. This model has been used in more than 150 countries around the world to simulate the atmosphere via real-time data [9]. In 2002, the Aviation Model (AVN) was developed by the National Centers for Environmental Prediction (NCEP) for short-range weather forecasting. This model (called the Global Forecasting System, GFS) is the leading forecasting model in the US [69]. A review of history of hydrometeorology is provided in Appendix A as supplementary materials.

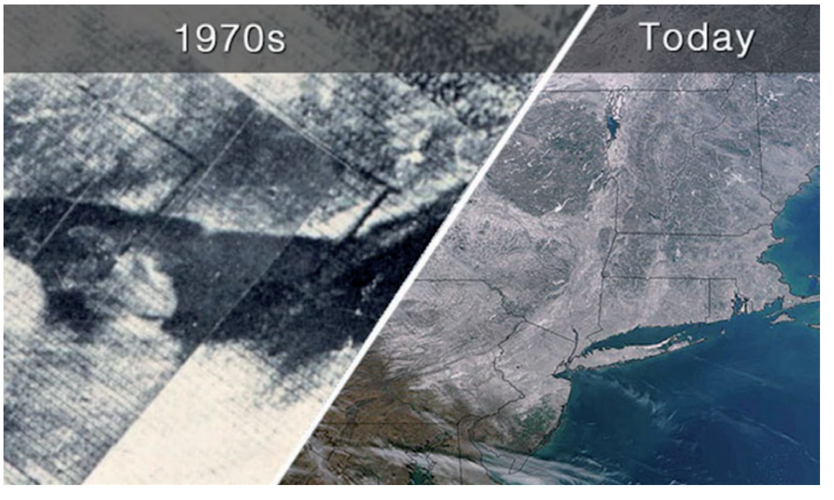

Figure 7.
The image of the Gulf of St. Lawrence from the (left) TIROS-1 weather satellite (1970s) and (right) S-NPP satellites (2013) [9].

a b

Figure 8.
(a) A monitoring site which is equipped with microwave sensors to provide real-time measurements of water level for forecasting storm surge [9], and (b) NASA's drone (Sierra) for remote sensing sampling in inaccessible regions such as polar regions, mountaintops, and open waters [70].

7. Emerging trends

Recent advances in active and passive remote sensing systems have created new cost-effective opportunities for meteorological applications. The new generation of satellites (e.g., Soil Moisture Active Passive (SMAP), Meteosat Third Generation (MTG), Himawari-9, and FY-4B satellites) allows monitoring the earth and atmosphere with higher spatial and temporal resolution. Progresses in technology have also improved field instruments used to collect weather data. In addition, numerical models have become more advanced as new theories and concepts were incorporated into them, allowing them to simulate hydrometeorological processes more accurately. At present, three-dimensional coupled atmosphere–ocean models use remotely sensed and in-situ observations to forecast weather up to ten-days ahead [9].

Weather modification by cloud seeding and aerosols spreading is one of the emerging trends to decelerate the threats associated with global warming [73]. The main purpose of cloud seeding and aerosols spreading is to alter rainfall patterns [73]. However, these methods are expensive and have not yet reached a practically acceptable level. In addition, the amount of precipitation that reaches the land surface is often negligible. This happens because snowfalls and/or light drizzles generated by the stratiform clouds are evaporated prior to reaching the ground level. To overcome this issue, stratocumulus clouds should be created that can have a global impact [74]. On the other hand, a number of scientists hypothesize that the weather modification can cause climate change and may lead to extreme weather events such as drought and flood [73, 75]. Some hydrometeorologists believe that the chemicals used in cloud seeding are dangerous for human health because of their toxicity and damage the ozone layer [75]. Moreover, the increase of particulate matters in the weather modification process may change the color of the sky from blue to gray [75].

Applying the science of hydrometeorology to real-world problems is another emerging trend. It is called operational hydrometeorology and deals with the application of hydrometeorology to real-time operational systems. The major components in an operational prediction system are monitoring equipment, meteorological and hydrological forecasting models, demand (water supply) prediction models, and decision support tools [76, 77]. The difficulty of forecasting rainfall has become a main challenge in the development of operational hydrometeorology [76]. There have been some attempts to overcome this issue. For example, the Flood Forecasting Center (FFC) was established in England and Wales in 2009 to forecast rainfall. A number of scientists used inverse modeling to predict rainfall [78–81]. For example, they assimilated river discharge observations within an ensemble data assimilation framework to predict rainfall [82–84]. Similarly, several studies assimilated soil moisture observations into water balance models to improve rainfall predictions [85–91].

Using low-cost sensors for flash flood forecasting [78], and application of hydrometeorology in marine sciences [92] and urban environment [80, 81] are other emerging trends.

8. Future issues and challenges

About 90% of disasters in the world during 1995–2015 were related to weather [93]. During this period, more than 600,000 people died, and more than 4 billion others were evacuated or injured because of weather-related hazardous events. The annual cost of damages caused by weather and climate extremes at the global scale is about $300 billion. Most disasters have been observed in the US, China, India, Philippines, and Indonesia [93].

Modern technologies such as advanced weather balloons, radars, satellites, and mathematical and numerical models have allowed to mitigate the impact of weather-related disasters on human beings and environment. In addition, innovative hydrometeorological devices and synoptic stations have provided concrete weather data to further lessen the effect of extreme weather events.

Despite these advances, the complexity of climate requires the development of more accurate models and instruments to manage the natural disasters more efficiently [9]. Overall, the future of the science of meteorology and hydrometeorology relies on new sophisticated instruments and prediction models, which enhance our ability to forecast weather and mitigate related hazards [9]. Having said that, the fourth industrial revolution (IR 4.0) may help the science of hydrometeorology by developing microchips, microcontrollers and more accurate sensors (i.e., multi-sensor meteorology) that can be utilized in weather sites [94–99].

Today, hydrometeorologists take advantage of satellite data at different spatial and temporal scales [100, 101]. Artificial intelligence (AI) and machine learning (ML) approaches can use long-term remotely sensed data from satellites to improve weather prediction and climate modeling capabilities [102–104]. Also, the advancement in Internet of Things (IoT) will make real-time data observations more precise [105–108].

9. Conclusions

This study provides a thorough review of the historical evolution of the science of hydrometeorology and its significant milestones from past civilizations to contemporary times. Hence, it can expand our knowledge of the advances in hydrometeorology through different centuries. In the past civilizations, the first steps were taken to understand weather changes. Today, the availability of robust numerical models, remote sensing data, and high computational capabilities have allowed humankind to predict meteorological and climatological events. Five major periods are considered in this study: 1) the prehistoric, 2) the archaic and medieval, 3) the early and mid-modern, 4) the modern, and finally 5) the contemporary periods. The key advancements and achievements in each period are presented.

The theocratic explanation of meteorology was dominant until the 7th century BC. In the prehistoric period, weather was unpredictable. Also, religion, folklore, tradition, culture, and beliefs were the main elements for studying hydrometeorology. In the late Archaic times, the Ionian philosophers explained hydrometeorological processes for the first time. Beginning in the historical period, Anaxagoras (*ca* 500–428 BC) used the ideas of the Ionian philosophers to develop rain gauge instruments in Athens. Also, in this period, the first evidence of measuring rainwater was seen in Greece and India. Later, Plato (*ca* 428–348 BC) developed the concept of the hydrological cycle in his academy in Athens. In the early Hellenistic times, Theophrastus of Eresos (*ca* 371–287 BC) wrote the book *Signs De Signis Tempestatum*, which was the first weather forecasting manual.

From 27 BC to 200 AD, Pomponius Mela, the Roman Emperor in Spain, worked on geographical maps and divided the earth into five climate zones. Investigating weather and atmospheric phenomena was almost stopped from the end of the Roman period to the Middle Ages of the Renaissance. However, there were considerable attempts from *ca* 1400 to 1900 AD to monitor hydrometeors and forecast weather by meteorological instruments, which were invented during this period.

From 1950 until present, theoretical approaches and mathematical analyses have been extensively used in the science of hydrometeorology. Sophisticated instruments have been developed to measure hydrometeorological variables. Computers have been utilized to solve complex mathematical equations and run numerical models to understand meteorological phenomena in the light of the application of meteorological theories (e. g., the application of heat and mass transfer theories to analyze evaporation).

The development of research and education in the field of hydrometeorology began after the Second World War, and accelerated with the formation of the World Meteorological Organization (WMO) in 1951. Scientists in the modern era have provided foundations for hydrometeorological investigations and instrumentations in a universal scale. Their efforts have improved humans' understanding of atmospheric phenomena.

The perspectives in the field of hydrometeorology are promising. This is mainly due to the advances in sensors and instrumentation, computational capabilities, remote sensing systems, data mining techniques, information and communication technologies (ICTs), decision support systems (DSS), and deep learning approaches. Although the science of hydrometeorology has significantly improved recently, there is still lack of adequate knowledge to accurately forecast extreme hydrometeorological events.

Appendix

Prehistoric times (*ca* 3500–750 BC)	
Ca 3500 BC	"Astrometeorology" emerged in Babylon. The sensitivity of humans to weather increased because they no longer migrated
Ca 3500 BC	Early Egyptians established sky-religion and rainmaking rituals
Ca 3000 BC	Nilometers were used to record water levels in the Nile River
Ca 1800 BC	Nilometers were developed at the second cataract of the Nile River
Ca 1750 BC	Water codes of King Hammurabi (*ca* 1792–1750 BC), which consisted of 282 regulations
Ca 740 BC	Nabu-nasir (*ca* 747–734 BC) regularly recorded movement and location of the moon. He also noted the times of sunrises, sunsets, and eclipses
Historical to medieval times (*ca* 750 BC-1400 AD)	
Ca 600 BC	The Thales of Miletus (*ca* 624–546), the founder of Ionian Stoa (School), is considered to be the father of natural philosophy and water science. He introduced the hydrologic cycle. He also presented a physical exegesis for the Nile flooding during summer time when rainfall in Egypt was minimal.
Ca 570 BC	Anaximander (*ca* 610–546 BC) explained the relationship between rainfall and evaporation in his book entitled "*On Nature*". The first known work on the natural philosophy.
Ca 550 BC	Anaximenes (585–528 BC) explained the formation of winds, clouds, rainfalls, and hails
End of *ca* 5th BC	Xenophanes (*ca* 570–475 BC) expressed the concept of hydrological cycle and the role of sea in it.
Ca 500 BC	First attempts to measure rainfall in Greece
Ca 465 BC	Anaxagoras (*ca* 500–428 BC) transferred the ideas of the Ionian philosophers to the Athenians. He also explained the formation of hailstorms.
Ca 400 BC	The first measurements of rain fall in India
Ca 400 BC	Hippocrates of Cos (*ca* 460–370 BC) studied the effects of climate and environment on human health in his treatise on *Airs, Waters, and Places*
Ca 387 BC	The Platonic Academy was founded by Plato (*ca* 428–348 BC). The concept of hydrological cycle was developed in that academy

Ca 345 BC	Aristotle (*ca* 384–322 BC) founded the Lykeion of Aristotle, also known as the "*Peripatec School*"
Ca 340 BC	Aristotle summarized his meteorological knowledge in his book entitled *Meteorologica*.
Ca 332 BC	Alexandria was founded in a small ancient Egyptian town by Alexander the Great
Ca 330 BC	Theophrastus of Eresos, Lesbos (*ca* 371–287 BC) Book on *Signs De Signis Tempestatum* is considered as the first weather forecasting manual
Ca 300 BC	Theophrastus On Winds (De Ventis) accepted the Presocratic's hypothesis of wind's origin. He also introduced a basic understanding of atmospheric pressure
Ca 250 BC	Archimedes (*ca* 287–212 BC) explained the buoyancy principle
Ca 240 BC	Eratosthenes (*ca* 276–194 BC) reported that the earth is a globe with the circumference of 40,000 km
Ca 240 BC	Philo of Byzantium (*ca* 280–220 BC) invented a device that measured the expansion and contraction of air as it warmed up and cooled down, respectively.
Ca 25 AD	In Spain, the Pomponius Mela, Roman Emperor introduced the climate zone systems
Ca 60 AD	Hero (Heron) of Alexandria (*ca* 10–75 AD) is mostly known as an engineer and designed a basic thermometer. Also, his treatise *Pneumatica* (Pneumatics) advanced the science of physics
Ca 70 AD	In Rome, Gaius Pliny Secundus (Pliny the Elder) (ca 23/24–79 AD) developed the encyclopedic Natural History, which later became an editorial version for encyclopedias
Ca 200 AD	In Tunisia, the Quintus Septimus Florens Tertullianus (160–225 AD) ended the observation-based science, and began the "sacred science" based on the "authority" of scripture
Ca 380 AD	Based on the prophecies of Isaiah and the Epistle to the Ephesians, St. Jerome (*ca* 347–420 AD) considered a doctrine of the diabolical origin of storms.
Ca 400 AD	In Algeria, St. Augustine, Bishop of Hippo (354–430 AD) whole heartedly supported the diabolical origin of storms.
Ca 900 AD	Chinese weighted charcoals to measure the air moisture
Ca 1000 AD	Ibn Wahshiyya translated the book entitled "*Nabataean Agriculture*". The importance of weather forecasting for agriculture was discussed in this book.
Ca 1247 AD	Gauges (made of large bamboo segments) were used to measure precipitation in China
Ca 1328 AD	William of Ockham (1285–1347 AD) attempted to advance natural sciences and atmospheric physics by improving the quality of observations.
Ca 1300 AD - 1400 AD	Air temperature (1400 BC) and rainfall (1216 BC) were recorded in ancient China
Early and mid-modern times (*ca* 1400–1800)	
Ca 1442	A simple cylindrical container was used to collect precipitation in Korea
Ca 1450	Leon Battista Alberti invented a flat plate anemometer in Italy
Ca 1450	Nicholas of Cusa invented a hygroscopic hygrometer
Ca 1500	Leonardo Da Vinci (1452–1519) improved the hygrometer, which was developed by Nicholas of Cusa
Ca 1593	Galileo Galilei (1564–1642) invented a thermometer in Italy
Ca 1639	Benedetto Castelli (1578–1643) constructed the first scientific rain gauge in Italy and Europe

Ca 1643	Evangelista Torricelli (1608–1647) invented the barometer
Ca 1648	Blaise Pascal (1623–1662) invented a barometer based on variations of atmospheric pressure with altitude
Ca 1660	Francesco Folli (1624–1685) created a paper-ribbon hygrometer, called *Mostra Umidaria*
Ca 1663	Robert Hooke (1635–1703) collaborated with Sir Christopher Wren to build the first automatic rain gauge called tipping bucket rain gauge. However, the first measurements of rainfall were done by Richard Towneley (1677–1704 AD)
Ca 1665	Grand Duke Ferdinand II de' Medici (1610–1670) created the condensation hygrometer
Ca 1667	Robert Hooke invented the anemometer
Ca 1670	Robert Hooke invented the first mercury glass-thermometer
Ca 1675	Horace-Benedict de Saussure (1740–1799) created the first hair hygrometer
Ca 1687	Isaac Newton (1643–1727) detailed his three laws of motion
Ca 1743	Benjamin Franklin (1706–1790) realized the northeastward movement of a hurricane from eclipse observations at Philadelphia and Boston.
Ca 1777	David Dobson developed the ideas to measure evaporation and raindrop size
Modern times (1800–1900)	
1818	Ernst Ferdinand August (1795–1870) developed ideas to create psychrometer
1820	John Frederic Daniell (1790–1845) invented a new hygrometer, called dew point hygrometer
1850	The British Meteorological Society was established and then renamed to Royal Meteorological Society (RMS)
1860	Meteorological observations were being made routinely by the Met Office in London
1861	William Jevons (1835–1882) reduced errors in rainfall measurements using a wind shield for rain gauges
1861	The Met Office began reporting weather forecasts for the public in England
1867	Father Secchi invented the first Meteorograph
1870's	Weather observations from 20 stations were transmitted to Washington DC via telegraph
1870	President Ulysses S. Grant established a weather bureau, which is now called the National Weather Service (NWS)
1870	Alexander Wilson used weather balloons in the UK to collect weather information
1873	The International Meteorological Organization was formed. It is now named the World Meteorological Organization (WMO) and is an entity of the United Nations
1879	George James Symons (1838–1900) expanded Jevons' theory and founded the British Rainfall Organization
1880's	The Meteorological Society of Japan were formed
1894	Weather kits were used to collect air temperature, pressure, humidity and wind speed at higher altitudes
1896	Léon Teisserenc de Bort (1855–1913), a French meteorologist, used weather balloons to measure air temperature and humidity
1898	The Richard brothers of France invented barothermograph

Contemporary times (1900-present)	
1907	Hugo Hildebrand Hildebrandsson (1838–1925) published his book entitled *International Cloud Atlas* and developed seasonal forecasts of clouds
1920's	Concepts of air masses and fronts were formulated by the Norwegian meteorologists. They developed a theory for the evolution of mid-latitude cyclones, which is still in use today
1921	Hydrometeorological Center of Russia was formed in Moscow
1921	The first weather radio broadcasts were made in the US
1922	Lewis Fry Richardson used numerical methods to forecast air temperature and humidity
1941	The US broadcasted the first TV program on weather forecast
1950	Jule Charney ran his meteorological algorithms by a computer called the Electronic Numerical Integrator And Computer (ENIAC)
1954	The first radar weather station was built in New Orleans, the US
1959	The Met Office created a computer (called Meteor), which was able to conduct 30,000 calculations every second
1960	The first weather satellite, called the Thermal Infrared Observation Satellite (TIROS), was launched by the US
1970's	NASA lunched geosynchronous weather satellites
1979	The first real-time medium-range forecasting model was developed by the European Centre for Medium-Range Weather Forecasts (ECMWF)
1988	The Intergovernmental Panel on Climate Change (IPCC) was founded by the United Nation
1990's	The NWS was modernized. The Weather Research and Forecasting (WRF) Model was developed.
2002	The Aviation Model (AVN) was created for short-range weather forecasting. This model, called the Global Forecasting System (GFS), is the leading forecasting model in the US.
2015	A new generation of supercomputers with the ability to perform over 10,000 trillion calculations per second was developed.

Table A.*1*.
Milestones in hydrometeorology in the (1) prehistoric times (ca 3500–750 BC), (2) historical to medieval times (ca 750 BC-1400 AD), (3) early and mid-modern times (ca 1400–1800), (4) modern times (1800–1900), and (5) contemporary times (1900-present).

Author details

Mohammad Valipour[1*], Sayed M. Bateni[1], Nicolas R. Dalezios[2], Mansour Almazroui[3], Essam Heggy[4,5], Zekai Şen[3] and Andreas N. Angelakis[6,7]

1 Department of Civil and Environmental Engineering and Water Resources Research Center, University of Hawaii at Manoa, Honolulu, HI 96822, USA

2 Department of Civil Engineering, University of Thessaly, Volos, Greece

3 Center of Excellence for Climate Change Research/Department of Meteorology, King Abdulaziz University, Jeddah 21589, Saudi Arabia

4 Viterbi School of Engineering, University of Southern California, Los Angeles, CA 90089, USA

5 Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

6 HAO-Demeter, Agricultural Research Institution of Crete, 71300, Iraklion, Greece

7 Union of Hellenic Water Supply and Sewerage Operators, 41222, Larissa, Greece

*Address all correspondence to: valipour@hawaii.edu

References

[1] Bruce JP, Clark RH. Introduction to Hydrometeorology: Pergamon International Library of Science, Technology. Amsterdam, Netherlands: Engineering and Social Studies. Elsevier; 2013

[2] Houser P. Hydroclimatology and hydrometeorology. International Encyclopedia of Geography: People, the Earth, Environment and Technology: People, the Earth, Environment and Technology. 2016;**1-13**

[3] Peck EL. Hydrometeorology. Bull. Am. Meteorol. Soci. 1978;**59**(5):609-612. DOI: 10.1175/1520-0477-59.5.609

[4] Rakhecha P, Singh VP. Applied Hydrometeorology. Berlin, Germany: Springer Science and Business Media; 2009

[5] Betts AK. Understanding hydro-meteorology using global models. Bull. Am. Meteorol. Soci. 2004;**85**(11):1673-1688. DOI: 10.1175/BAMS-85-11-1673

[6] Collier CG. Hydrometeorology. Hoboken, NJ: John Wiley and Sons; 2016

[7] Fry JL, Graf HF, Grotjah R. The Encyclopedia of Weather and Climate Change. Los Angeles: University of California Press; 2010

[8] Shuttleworth WJ. Terrestrial Hydrometeorology. Hoboken, NJ: John Wiley and Sons; 2012

[9] Teague KA, Gallicchio N. The Evolution of Meteorology: A Look into the Past, Present, and Future of Weather Forecasting. Hoboken, NJ, USA: John Wiley and Sons; 2017

[10] Margulis SA, Wood EF, Troch PA. The terrestrial water cycle: Modeling and data assimilation across catchment scales. Journal of Hydrometeorology. 2006;**7**(3):309-311. DOI: 10.1175/JHM999.1

[11] Krasilnikoff J, Angelakis AN. Water management and its judicial contexts in ancient Greece: A review from the earliest times to the Roman period. Water Polic. 2019. DOI: 10.2166/wp.2019.176

[12] Teresi D. Lost Discoveries: The Ancient Roots of Modern Science: From the Babylonians to the Maya. New York: Simon and Schuster; 2002

[13] Verderame L. The halo of the moon. In: Fincke JC, editor. Divination in the Ancient near East. Winona Lake, IN: Eisenbraun; 2014

[14] Burnet J. Early Greek Philosophy. 3rd ed. London, UK: A and C Black; 1920

[15] Angelakis, A. N., Asano, T., Bahri, A., Jimenez, B. E., and G. Tchobanoglous, G.: Water Reuse: From ancient to the modern times and future. Front. Environ. Sci. 6:26. doi:10.3389/fenvs.2018.00026, 2018.

[16] Bulu A. Historical development of hydrology. BALWOIS, Ohrid, North Macedonia. 2010;**9**

[17] Shamasastry R. Translation of 'Arthasastra' by Kautilya. Gov. Oriental Library Series, Bibliotheca Sanskrita, No. 37, Part 2. Bangalore; 1915

[18] Danby H. Translation of 'the Mishnah'. Oxford, UK: Oxford University Press; 1933

[19] Biswas, A. K.: A Short History of Hydrology, The Progress of Hydrology, Proceedings of the First International Seminar for Hydrology Professors, Volum II., 914-934, University of Illinois, Illinois, USA, 1969.

[20] Hollar S. Inventors and Innovations: Pioneers in the World of Weather and Climatology. New York: Britannica Educational Publishing in Association with Rosen Educational Services; 2013

[21] Koutsoyiannis, D.: Water control in the Greek cities. Water systems and urbanization in Africa and beyond Uppsala, Univ. of Uppsala, Sweden, 1-2 March 2012, 2012.

[22] Koutsoyiannis, D. and Angelakis, A. N.: Hydrologic and Hydraulic Sciences and Technologies in Ancient Greek Times. The Encycl. of Water Sci., Markel Dekker Inc., (B.A. Stewart and T. Howell, Eds.), Madison Ave. New York, N.Y., USA, 415-417, 2003.

[23] Koutsoyiannis D, Mamassis N, Tegos A. Logical and illogical exegeses of hydrometeorological phenomena in ancient Greece. Water Science and Technology: Water Supply. 2007;**7**(1):13-22. DOI: 10.2166/ws.2007.002

[24] Webster EW. Meteorologica. In: Ross WD, editor. The Works of Aristotle, Vol. 3. Oxford: Clarendon Press; 1955

[25] Horstmeyer, S. L.: An Outline of the History of Meteorology, available online: http://www.shorstmeyer.com/msj/geo165., 56, 2005.

[26] The Irish Times: Pliny the Elder: Sailor and Meteorologist. https://www.irishtimes.com/news/pliny-the-elder-sailor-and-meteorologist-1.219939 (assessed 3/28/2020), 2020.

[27] Papadopoulos E. Heron of Alexandria (c. 10-85 AD). Athens, Greece: National Technical Univ. of Athens; 2007

[28] Koutsoyiannis, D. and Patrikiou, A.: Water control in Ancient Greek cities. In: Water and Urbanization, T. Ostigard, (ed.). 130-148, 2013.

[29] Strangeways I. Improving precipitation measurements. International Journal of Climatology. 2004;**24**(11):1443-1460. DOI: 10.1002/joc.1075

[30] Strangeways I. A History of Raingauges. TerraData Ltd., http://www.rmets.org/sites/default/files/pdf/presentation/20100417-strangeways.pdf, (accessed 10 May 2015); 2010

[31] Hameen-Anttila J. The Last Pagans of Iraq: Ibn Wae Shiyya and his Nabatean Agriculture. Leiden, The Netherlands: Koninklijke Brill NV; 2006

[32] Hirschberger J. A Short History of Western Philosophy. Boulder, CO: Westview Press; 1977

[33] Reynolds R, Hammond JC, Smith F, empest S. In: Gilbert R, John D, Colson RS, et al., editors. Eyewitness Companions: Weather-Forecasting, Weather Phenomena, Climate Change, Meteorology. New York: Dorling Kindersley Publishing; 2008

[34] Gallica: Les Meteores. https://gallica.bnf.fr/ark:/12148/btv1b86069594/f243.item (assessed 3/28/2020), 2020.

[35] Bernal A. Q: Discover ideas about Weather Predictions. https://www.pinterest.es/pin/495325659001964022/ (assessed 3/5/2020), 2020.

[36] Ferrari, J.: Un breve cenno alla storia. http://pcfarina.eng.unipr.it/DispenseArch00/ferrari/ferrari.htm (assessed 3/5/2020), 2000.

[37] Francesco Folli's Hygrometer: http://himetop.wikidot.com/francesco-folli-s-hygrometer (assessed 6/15/2020), 2020.

[38] Weissman SA. Temperatures near the absolute zero. American Journal of Physics. 1947;**15**(6):451-457

[39] Piana ME. Hadley Cells. Harvard Press. https://www.seas.harvard.edu/climate/eli/research/equable/hadley.html (assessed 3/28/2020); 2020

[40] Darrigol O, Frisch U. From Newton's mechanics to Euler's equations. Physica D: Nonlinear Phenomena. 2008;**237**(14-17):1855-1869. DOI: 10.1016/j.physd.2007.08.003

[41] Allaby M. Dangerous Weather: A Chronology of Weather. Inc, New York, USA: Facts on File; 1998

[42] Biswas, A. K.: The Automatic Rain-Gauge of Sir Christopher Wren, F.R.S., Notes and Records of the Royal Society of London, 22 (1/2), Royal Society, 94-104, 1967.

[43] Thayer, B.: Theophrastus. De Signis by Theophrastus. Published in Vol. II of the Loeb Classical Library Edition of the Enquiry into Plants, 1926, http://penelope.uchicago.edu/Thayer/E/Roman/Texts/Theophrastus/De_signis*.html, (accessed 4 April 2015), 2012.

[44] Walker G. An Ocean of Air: A Natural History of the Atmosphere. London, UK: Bloomsbury; 2010

[45] Elsin, H.: Nilometer. In: Encyclopaedia of the History of Science, Technology, and Medicine in Non-Western Cultures (H. Selin, Ed.). Springer Netherlands, Absterdam, The Netherlands, p. 1753, 2008.

[46] The Editors of Encyclopaedia Britannica. John Frederic Daniell: British Chemist. Encyclopaedia Britannica, www.britannica.com/EBchecked/topic/151016/John-Frederic-Daniell, (accessed 10 May 2015); 2015

[47] Rainfall B. On the distribution of rain in space and time over the British Isles during the year 1908 as recorded by more than 4500 observers in Great Britain and Ireland, and discussed with articles upon various branches of Rainfall work. Nature. 1909;**81**:514-515. DOI: 10.1038/081514b0

[48] Pedgley DE. A short history of the British Rainfall organisation. Journal of Meteorology. 2003;**28**(276):74-75. DOI: 10.1002/wea.579

[49] Dalezios NR. Evolution of meteorology: From aristotle to satellites, proceedings of the 1st IWA regional symposium on water. Wastewater and Environment, Patras, Greece. 2014;**201-211**

[50] Dalezios NR, Nastos P. Milestones of the diachronic evolution of meteorology. Intern. J. Global Environ. Issues. 2016;**15**(1/2):49-69. DOI: 10.1504/IJGENVI.2016.074363

[51] Monmonier M. Air Apparent: How Meteorologists Learned to Map, Predict, and Dramatize Weather. Chicago: University of Chicago Press; 1999

[52] Walker M. History of the Meteorological Office. New York: Cambridge University Press; 2012

[53] Brassart, F.: Meteorograph by Secchi. Museum of INAF-Rome Astronomical Observatory, Monte Porzio Catone. Roma. https://tracieloeterra.bicentenarioangelosecchi.it/glistrumenti/dry-meteorograph/?lang=en (assessed 3/5/2020), 1867.

[54] Atlas Abscura: Meteorological Pillar of the 19th Century. https://www.atlasobscura.com/places/meteorological-pillar-of-the-19th-century (assessed 3/8/2020), 2020.

[55] History of the National Weather Service. Public Affairs Office, NWS and NOAA, http://www.nws.noaa.gov/pa/history/, (accessed 1 May 2015); 2012

[56] DuBois J, Multhauf R, Ziegler C. The Invention and Development of the Radiosonde, with a Catalog of Upper-Atmospheric Telemetering Probes in the National Museum of American History: Smithsonian Institution. Washington DC: Smithsonian Institution Press; 2002

[57] Jewell R. The Bergen School of Meteorology: The cradle of modern weather-forecasting. Bull. Am. Meteorol. Soci. 1981;**62**(6):824-830. DOI: 10.1007/BF00878151

[58] Donn ML. Meteorology. 4th ed. New York: McGraw-Hill Book Company; 1975

[59] Lee HDP. Aristotle: Meteorologica, Loeb Classical Library No. 397. Cambridge and London: Harvard University press and Heinemann; 1952

[60] Hugo Hildebrand Hildebrandsson. Encyclopedia Britannica 1911. ITA, www.theodora.com/encyclopedia/h2/hugo_hildebrand_hildebrandsson.html, (accessed 27 April 2015); 2011

[61] Overview of the Met Office: (Updated 2012) Met Office, Met Office, http://www.metoffice.gov.uk/news/in-depth/overview, accessed 15 September 2015, 2015.

[62] Barnett C. Rain: A Natural and Cultural History. New York: Crown Publishers; 2015

[63] Supercomputers: Met Office, http://www.metoffice.gov.uk/news/in-depth/supercomputers, (accessed 2 July 2015), 2014.

[64] Henson R. Weather on the Air: A History of Broadcast Meteorology. Boston, USA: American Meteorological Society; 2010

[65] Cobb A. Weather Observation Satellites. New York: The Rosen Publishing Group, Inc.; 2003

[66] Stunder B. What Is the Difference between the AVN, MRF, and GFS Models? Air Resources Laboratory, NOAA, https://www.ready.noaa.gov/faq_md15.php, (accessed 11 September 2015); 2010

[67] AghaKouchak A, Farahmand A, Melton FS, Teixeira J, Anderson MC, Wardlow BD, et al. Remote sensing of drought: Progress, challenges and opportunities. Reviews of Geophysics. 2015;**53**(2):452-480. DOI: 10.1002/2014RG000456

[68] Sun Q , Miao C, Duan Q , Ashouri H, Sorooshian S, Hsu KL. A review of global precipitation data sets: Data sources, estimation, and intercomparisons. Reviews of Geophysics. 2018;**56**(1):79-107. DOI: 10.1002/2017RG000574

[69] Bruintjes, R., and Terblanche, D.: Report of the Expert Team on Weather Modification Meeting, WMO and ETMW, Phitsanulok, Thailand, 17-19 March 2015, 4-6, 2015.

[70] Levine, J.: NASA's Ikhana Could Fly in the NAS Unaccompanied in 2018. https://www.nasa.gov/centers/armstrong/feature/Ikhana_could_fly_unaccompanied_in_2018.html (assessed 3/8/2020), 2018.

[71] Kumar R, Bahuguna IM, Ali SN, Singh R. Lake inventory and evolution of glacial lakes in the Nubra-Shyok basin of Karakoram range. Earth Sys. Environ. 2020;**4**(1):57-70. DOI: 10.1007/s41748-019-00129-6

[72] Saleem A, Dewan A, Rahman MM, Nawfee SM, Karim R, Lu XX. Spatial and temporal variations of erosion and accretion: A case of a large Tropical River. Earth Sys. Environ. 2020;**4**(1):167-181. DOI: 10.1007/s41748-019-00143-8

[73] Goodell J. How to Cool the Planet: Geoengineering and the Audacious Quest to Fix Earth's Climate. Boston, Massachusetts and New York, New York: Houghton Mifflin Harcourt; 2010

[74] Wigington, D.: Global Weather Modification Assault Causing Climate Chaos and Environmental Catastrophe, Geoengineering Watch, http://www.geoengineeringwatch.org/global-weathermodification-assault-causing-climate-chaosand-environmental-catastrophe-2/, (accessed 18 March 2016), 2014.

[75] Dale, M., Davies, P. and Harrison, T.: February. Review of recent advances in UK operational hydrometeorology, Proceed. Institution Civil

Engineers-Water Manage. 165, 2, 55-64, doi:10.1680/wama.2012.165.2.55, 2012.

[76] Sene K. Hydrometeorology-Forecasting and Applications. New York: Springer; 2010

[77] Zanchetta AD, Coulibaly P. Recent advances in real-time pluvial flash flood forecasting. Water. 2020;**12**(2):570. DOI: 10.3390/w12020570

[78] Fang MC, Tsai KY, Fang CC. The effect of hydrometeorology on ship collision avoidance in heavy traffic areas with a simplified simulation model. J. Marine Sci. Technol. 2019;**27**(3):235-245. DOI: 10.6119/JMST.201906_27(3).0006

[79] Ntelekos AA, Smith JA, Baeck ML, Krajewski WF, Miller AJ, Goska R. Extreme hydrometeorological events and the urban environment: Dissecting the 7 July 2004 thunderstorm over the Baltimore MD metropolitan region. Water Resources Research. 2008;**44**(8). DOI: 10.1029/2007WR006346

[80] Sawada Y, Nakaegawa T, Miyoshi T. Hydrometeorology as an inversion problem: Can river discharge observations improve the atmosphere by ensemble data assimilation? Journal of Geophysical Research – Atmospheres. 2018;**123**(2):848-860. DOI: 10.1002/2017JD027531

[81] Yang J, Wang ZH, Georgescu M, Chen F, Tewari M. Assessing the impact of enhanced hydrological processes on urban hydrometeorology with application to two cities in contrasting climates. Journal of Hydrometeorology. 2016;**17**(4):1031-1047. DOI: 10.1175/JHM-D-15-0112.1

[82] Crow WT, Huffman GF, Bindlish R, Jackson TJ. Improving satellite-based rainfall accumulation estimates using spaceborne soil moisture retrievals. Journal of Hydrometeorology. 2009;**10**:199-212. DOI: 10.1175/2008JHM986

[83] Herrnegger M, Nachtnebel HP, Schulz K. From runoff to rainfall: Inverse rainfall-runoff modeling in a high temporal resolution. Hydrol. Earth Sys. Sci. 2015;**19**:4619-4639. DOI: 10.5194/hess-19-4619-2015

[84] Vrugt JA, ter Braak CJF, Clark MP, Hyman JM, Robinson BA. Treatment of input uncertainty in hydrologic modeling: Doing hydrology backward with Markov chain Monte Carlo simulation. Water Resources Research. 2008;**44**:W00B09. DOI: 10.1029/2007WR006720

[85] Aubert D, Loumagne C, Oudin L. Sequential assimilation of soil moisture and streamflow data in a conceptual rainfall-runoff model. Journal of Hydrology. 2003;**280**(1-4):145-161. DOI: 10.1016/S0022-1694(03)00229-4

[86] Brocca L, Ciabatta L, Massari C, Moramarco T, Hahn S, Hasenauer S, et al. Soil as a natural rain gauge: Estimating global rainfall from satellite soil moisture data. J. Geophysic. Res. Atmos. 2014;**119**:5128-5141. DOI: 10.1002/2014JD021489

[87] Brocca L, Moramarco T, Melone F, Wagner W. A new method for rainfall estimation through soil moisture observations. Geophysic. Res. Let. 2013;**40**:853-858. DOI: 10.1002/grl.50173

[88] Brocca L, Moramarco T, Melone F, Wagner W, Hasenauer S, Hahn S. Assimilation of surface-and root-zone ASCAT soil moisture products into rainfall-runoff modelling. IEEE Transact. Geosci. Remote Sens. 2011;**50**(7):2542-2555. DOI: 10.1109/TGRS.2011.2177468

[89] Crow WT, van den Berg MJ, Huffman GJ, Pellarin T. Correcting rainfall using satellite-based surface soil moisture retrievals: The soil moisture analysis Rainfall tool (SMART). Water Resources Research. 2011;**47**:W08521. DOI: 10.1029/2011WR010576

[90] Koster RD, Brocca L, Crow WT, Burgin MS, De Lannoy GJM. Precipitation estimation using L-band and C-band soil moisture retrievals. Water Resources Research. 2016;**52**:7213-7225. DOI: 10.1002/2016WR019024

[91] Mohammed, K., Leconte, R. and Trudel, M.: January. Data Assimilation of Remotely Sensed Soil Moisture in Hydrological Modeling to Improve Flood Forecasting. In 100th American Meteorological Society Annual Meeting. AMS, 2020.

[92] Wu DS, Wang WJ, Yu SB, Zhou SH, Zhang J. Study on relationship between red tide of year 2002 in Guangdong coastal water and the marine hydro-meteorology. J. Tropic. Meteorol. 2011;**27**:271-277

[93] UNISDR (United Nation Office for Disaster Risk Reduction). The Human Cost of Weather-Related Disasters 1995-2015. The Centre for Research on the Epidemiology of Disasters (CRED), United Nation Office for Disaster Risk Reduction (UNISDR). Available via DIALOG. http://www.unisdr.org/2015/docs/climatechange/COP21_WeatherDisastersReport_2015_FINAL.pdf. (Accessed 19 Sept 2020); 2015

[94] Mao, H., Paul, O. K., Yang, N. and Li, L.: Smart Arduino Sensor Integrated Drone for Weather Indices: Prototype. In Drones-Applications. IntechOpen. Drones: Applications (Editor: George Dekoulis). Electronic book. ISBN: 178923284, 2018.

[95] Monmonier M. Air Apparent: How Meteorologists Learned to Map, Predict, and Dramatize Weather. Chicago, USA: University of Chicago Press; 2000

[96] Moore RR, Collins MD, Moore RR, Collins MD. Personal severe weather warning microchip and pressure sensor. U.S. Patent. 2006;7:066,020

[97] Vas Á, Fazekas Á, Lehotai B, Nagy G, Tóth L. Microcontroller-based network for meteorological sensing and weather forecast calculations. Carpathian Journal of Electronic and Computer Engineering. 2012;**5**:139

[98] Willis PA, Creamer JS, Mora MF. Implementation of microchip electrophoresis instrumentation for future spaceflight missions. Analytic. Bioanalytic. Chem. 2015;**407**(23):6939-6963. DOI: 10.1007/s00216-015-8903-z

[99] Zheng S, Wang G, Huang X, Miao C, Xing W, Chen S, et al. Improvement and Design of Transmitter Modifier Wind Cooling Protection for CINRAD/CB weather radar. J. Geosci. Environ. Protect. 2018;**6**(11):139-146. DOI: 10.4236/gep.2018.611011

[100] Almazroui, M., Saeed, S., Saeed, F., Islam, M. N. and Ismail, M.: Projections of Precipitation and Temperature over the South Asian Countries in CMIP6. Earth Sys. Environ., 4(2), 297-320, doi:10.1007/s4174 8-020-00157-7, 2020a.

[101] Almazroui, M., Saeed, F., Saeed, S., Islam, M. N., Ismail, M., Klutse, N. A. B. and Siddiqui, M. H.: Projected Change in Temperature and Precipitation Over Africa from CMIP6. Earth Sys. Environ., 1-21, doi:10.1007/s00704-015-1715-4, 2020b.

[102] Anandharajan, T. R. V., Hariharan, G. A., Vignajeth, K. K. and Jijendiran, R.: Weather monitoring using artificial intelligence. In 2016 2nd international conference on computational intelligence and networks (CINE) (106-111). IEEE, 2016.

[103] Liu, J. N., Hu, Y., He, Y., Chan, P. W. and Lai, L.: Deep neural network modeling for big data weather forecasting. In Information Granularity, Big Data, and Computational Intelligence (389-408). Springer, Cham, 2015.

[104] McGovern A, Elmore KL, Gagne DJ, Haupt SE, Karstens CD, Lagerquist R, et al. Using artificial

intelligence to improve real-time decision-making for high-impact weather. Bull. Am. Meteorol. Soci. 2017;**98**(10):2073-2090. DOI: 10.1175/BAMS-D-16-0123.1

[105] Carranco JS, Salgado FD, Sellers C, Torres H. Comparative Analysis of Meteorological Monitoring Using an Integrated Low-Cost Environmental Unit Based on the Internet of Things (IoT) with an Automatic Meteorological Station (AWS), In 2017 IEEE Second Ecuador Technical Chapters Meeting (ETCM) (1-6). IEEE; 2017

[106] Kavitha, N. and Madhumathy, P.: Development of an IOT-Based Atmospheric Fine Dust Monitoring System. In Internet of Things, Smart Computing and Technology: A Roadmap Ahead (263-279). Springer, Cham, 2020.

[107] Onal AC, Sezer OB, Ozbayoglu M, Dogdu E. December. Weather data analysis and sensor fault detection using an extended IoT framework with semantics, big data, and machine learning. In: 2017 IEEE International Conference on Big Data (Big Data) (2037-2046). IEEE. 2017

[108] Pradeep, S. and Sharma, Y. K.: Storing live sensor data to the platforms of internet of things (IoT) using Arduino and associated microchips. In Proceedings of the Third International Conference on Computational Intelligence and Informatics (1-15). Springer, Singapore, 2020.