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FACTORS AFFECTING VARIATIONS IN THE HYDROLOGICAL CYCLE AT DIFFERENT TEMPORAL AND SPATIAL SCALES

DEJAVNIKI, KI VPLIVAJO NA SPREMEMBE V HIDROLOŠKEM KROGU V RAZLIČNIH ČASOVNIH IN PROSTORSKIH MERILIH

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Abstract

The climate is changing intensively, causing major variations in the local, regional, and eventually global hydrological cycle. Furthermore, climate changes strongly affect individual components of the hydrological cycle. The prevailing present-day opinion is that climate change is primarily caused by anthropogenic production of CO_2. This assumption is automatically accepted as the main reason or at least a contributory cause of changes in the hydrological cycle. However, changes in hydrological cycle appear to be a significantly more complex problem. At the same time, various other processes take place on different temporal and spatial scales. The article discusses numerous natural and human-caused factors that can affect changes in the hydrological cycle. When considering the factors that affect the planetary hydrological cycle on any temporal or spatial scale, it is necessary to consider many potential causes and understand their interactions. The natural factors discussed in this paper are Milanković cycles, Wolf number, Hurst phenomenon, earthquakes, volcanoes, and meteorite impacts. Among the anthropogenic influences, the role of dams and reservoirs is emphasized.

Keywords: Hydrological processes, Milanković cycles, volcanoes, El Niño and La Niña, earthquakes, Wolf number, Hurst phenomenon, dams and reservoirs.

Izvleček

Podnebje se intenzivno spreminja, kar povzroča velike spremembe v lokalnem, regionalnem in navsezadnje globalnem hidrološkem krogu. Podnebne spremembe močno vplivajo tudi na posamezne dele hidrološkega kroga. Danes prevladuje mnenje, da podnebne spremembe povzroča predvsem antropogena proizvodnja CO_2. Ta predpostavka je samodejno privzet kot poglavitni ali vsaj prispevajoči vzrok za spremembe v hidrološkem krogu. A zdi se, da so spremembe hidrološkega kroga bistveno bolj zapleten problem. Hkrati se na različnih časovnih in prostorskih ravneh odvijajo različni procesi. V članku so obravnavani številni naravni in človeški dejavniki, ki lahko vplivajo na spremembe hidrološkega kroga. Pri obravnavi dejavnikov, ki vplivajo na planetarni hidrološki krog v katerem koli časovnem ali prostorskem merilu, je treba upoštevati številne možne

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vzroke in razumeti njihovo medsebojno delovanje. Naravni dejavniki, obravnavani v tem prispevku, so Milankovićevi cikli, Wolfovo število, Hurstov pojav, potresi, vulkani in padci meteoritov. Med antropogenimi vplivi je poudarjena vloga jezov in zadrževalnikov.

Ključne besede: Hidrološki procesi, Milankovićevi cikli, vulkani, El Niño in La Niña, potresi, Wolfovo število, Hurstov pojav, pregrade in zadrževalniki.

1. Introduction

Climate changes are a normal part of the Earth's natural variability caused by the interaction of the atmosphere, oceans, and land, and changes in the amount and angle of the radiation from the Sun reaching the planet's surface. Any factor affecting the Earth's radiation balance can affect the global climate (Kumar and Singh, 2019). The earth's hydrological cycle links interactions between the atmosphere, lithosphere, biosphere, and anthroposphere, and it is also profoundly affected by human activities and socio-economic development (Yang et al., 2021).

One of the biggest challenges in modern science is researching and explaining the main mechanisms controlling global climate change on Earth. Indeed, in recent decades the endeavors of scientific community have been focused on understanding, explaining, and predicting the future development of the climate on planet Earth. The emphasis is on predicting the consequences of the increase in CO_2 concentration in the atmosphere caused by anthropogenic emissions. Since the general public is involved in this global process, it has become particularly interesting for politicians, a situation that generally does not lead to objective explanations and assessments, and thus similarly fails to lead to effective solutions to the crisis we are witnessing. Climate change, with its most pronounced consequence, the global increase in air temperature, directly affects the hydrological cycle. In this paper, we will try to consider factors affecting the variations in the Earth's hydrological cycle on several scales, firstly temporally and then spatially.

The analysis herein focuses on the last hundred years, when the consequences of climate change have been most strongly felt, and, at the same time, when anthropogenic influences grew to unimaginable limits. This recent period is also known as the Anthropocene (Lewis and Maslin, 2015). In addition to natural processes, numerous human activities on Earth affect and change not only the local environment but also regional and global phenomena, and the hydrological cycle is affected accordingly. The evidence of human influence on the planet is ample but, geologically speaking, all these changes have taken place in recent times, especially intensively in the last few hundred years. The best-known and best-studied processes, as elucidated through measurement, are those of the last two hundred years. However, humans began affecting the planet's environment much earlier, almost at the very beginning of their existence. This influence intensified when we stopped living in nomadic groups and began engaging in agriculture on a vast scale.

It is a process that has been going on for several thousand years, and there is evidence that it has taken place intensively during the entire Holocene period, the post-Pleistocene geological period of the Quaternary, the present-day geological period of the past 12,000 years. Urbanization can be an example of the local scope of human activities. Mass deforestation with mass agricultural production, river flow regulation, and dam construction affect regional changes. An example of global influence is the anthropogenic emission of greenhouse gases, which is considered a key influence on global warming. The amount of such emissions started increasing drastically during the industrial revolution around the second half of the 18th century. It is important to emphasize that the Anthropocene epoch significantly accelerates the anthropogenic influence on climate change.

When considering the factors that affect the planetary hydrological cycle on any temporal or spatial scale, it is necessary to consider many potential causes, some of which appear simultaneously and last for more or less time than others. Some of their consequences are felt immediately, and others appear only after some time. This paper will touch upon all the factors that influence climate change and consequently the variations of the hydrological cycle. It further discusses the possible and still mostly neglected role of the Wolf number on the processes affecting the planetary variations in the hydrological cycle.

Since this is an extremely complex issue with many more questions raised and not many reliable and scientifically based answers found, the author welcomes any criticism and discussion about the views presented in this paper.

2. Natural phenomena that influence variations in the hydrological cycle

The discussion of this topical issue will begin with a brief review of how Milanković's theory of the Earth’s movement drives collective climatic effects (https://earthobservatory.nasa.gov/features/Milankovitch/milankovitch_2.php). The theory links climate change to changes in orbital eccentricity, axis tilt, and precession, all of which processes take place simultaneously. The full precession cycle of the Earth's axis takes about 26,000 years. The elliptical orbit rotates in a cycle lasting 23,000 years. The angle between the Earth's axis of rotation and the normal to the orbital plane oscillates between 22.1° to 24.5° with a period of 41,000 years. Milanković studied the inclination of the Earth's orbit, which oscillates in relation to the angular momentum of the solar system with a period of approximately 70,000 years. It turned out that this movement is well correlated with the occurrence of ice ages. The Milanković cycles therefore denote periodic changes in the Earth's orbital characteristics, thus controlling the amount of solar energy received. In this way, they influence the climate on a scale of several tens of thousands of years. Although they have no (or, at the most, a negligible) influence on the current form of climate change, they are believed to have dictated the Earth's climate for millions of years, affecting hundreds to thousands of years of glacial and interglacial periods, and therefore the one we are in right now.

The relationship between the hydrological cycle and the temperature is extremely complex and not sufficiently understood. Gaining a better understanding of the many existing feedbacks is of great importance. Pratap and Markonis (2022) warn that the exact magnitude of the hydrological cycle’s response and its spatio-temporal characteristics are still being researched. In Earth’s hydroclimatic history, there have been some periods where the global temperature was substantially different than it is at present; further, there have been substantial shifts in the hydrological cycle (Ljungqvist et al., 2016).

Figure 1 shows a graph of the estimated temperature change on Earth starting from 1993 and going backward for the past 100,000 years. The chart was created as a part of the multinational GRIP (Greenland Ice Core Project) project (Stauffer, 1993). The ice crust at the poles consists of stratified layers of precipitation deposited over the past several hundred thousand years. By analyzing the chemical and physical properties of the 3029 m of ice crust extracted in the central part of Greenland, it is possible to reconstruct in detail the climate as it was in the past. It is noticeable that, just in the last 10,000 years or so, the temperature on Earth has varied within narrow limits of about ±1 ºC. Before that time, the temperature was lower and varied between -2 ºC and -20 ºC compared to present temperature averages. It is interesting to emphasize that scientists explain the sudden drop in temperature about 75,000 years ago through the eruption of the supervolcano Toba in present-day Indonesia (Robock et al., 2009; Bonacci, 2014).

Volcanic activity has also contributed significantly to cold climate periods during the Holocene. Eruptions trigger a chain of events that have a large impact on the climate, causing relatively short-term cooling lasting from several months to several years, depending on the scale of the eruption and the amount of ejected material. They cause strong desert storms and the occurrence of red rains, precipitation that is rich in iron oxides and phosphates, which act as fertilizer in the oceanic biosphere. This results in phytoplankton and zooplankton blooms, which constantly absorb CO_2. During periods of weaker volcanic activity, CO_2 slowly returns to the atmosphere, and the Earth is rewarmed (Issar, 2003; Cole-Dai, 2010).

The climate has changed significantly during the Holocene, affecting the hydrological cycle. The impact was felt differently in various regions, with different scales of change in temperature and humidity (Issar, 2003). In the Mediterranean, western and central Europe, and the western USA, the climate's cooling was accompanied by an increase in precipitation and the intensification of the hydrological system. The term intensification of the hydrological cycle is used to describe an acceleration in the rates of atmospheric water vapor content, precipitation, evaporation, and evapotranspiration. At higher latitudes and longitudes, this cooling led to the formation of glaciers that caused a reduction in precipitation, resulting in the desertification of the areas along the edges of existing deserts (Issar, 2003). The warmest Holocene period in Europe was between 10,000 and 6,000 years ago. It was called the Holocene Thermal Optimum. At that time, the Sahara was not a desert (Bonacci and Roje-Bonacci, 2022). The large river Tamanrassett flowed through its central and western parts (Bonacci, 2015), and there were some open watercourse systems in the southwestern part of the Sahara, today's Wadi Howarna (Pachur and Kröpelin, 1987). A long cooling period followed, and the temperature during the 3rd and 2nd millennium BCE was 2 ºC to 3 ºC lower than it is today (Pachur and Kröpelin, 1987).

Figure 2 shows a graph of the sea level over the last 120,000 years. It can be seen that a level approximately similar to today's was reached around 8,000 years ago. Regarding Figure 2, there are photographs of drawings discovered in two caves in the karst area of France, namely Lascaux and Chauvet-Pont-d'Arc. The drawings of the animals in these caves can be associated with the climatic conditions that prevailed at the time of their making. What is intriguing is the fact that the paintings in the Lascaux cave were made about 4,000 years after the maximum of the last ice age, while the drawings in the Chauvet Pont-d'Arc cave date more than 10,000 years before that maximum (Bonacci, 2016).

During the last ice age, enormous ice fields formed a natural dam and blocked the flow of rivers flowing toward the northern seas. Today's Siberian rivers (Ob, Irtysh, Yenisei, Lena, Kolyma, etc.) overflowed along the glaciers, forming gigantic lakes connected to periglacial meltwater runoff systems. A similar system of glacial lakes existed in North America. About 21,000 years ago, the level of the planetary oceans was about 130 meters lower than it is today. The last ice age, within the Pleistocene or Quaternary Ice Age, began about 110,000 years ago and ended about 9700-9600 BC. The last glacial maximum, when the total volume of ice in the glaciers was the greatest ever, dates to about 26,000 to 20,000 years ago. The last ice age ended about 10,000 years BC. Then the ice retreated to its current limits, and the climate-vegetation belts as we know today were formed.

El Niño and La Niña are climate patterns in the Pacific that affect weather across the planet. These patterns are extensive, long-term changes in sea surface temperature and motion in the entire equatorial part of the Pacific Ocean. During El Niño, a warm current occurs off the coast of Ecuador and Peru around Christmastime. It brings wet and rainy weather, floods in otherwise dry areas of South America, and a dry period in Indonesia. When El Niño culminates, waves are formed in the ocean that, after a year or two, lead to a cooling of the eastern Pacific, strengthening of the trade winds, and the appearance of La Niña. La Niña favors the creation of waves that eventually cause the eastern Pacific to warm, trade winds to weaken, and El Niño to develop. The occurrence is not periodic. Certain extremes occur with an interval of 2 to 10 years. A typical interval between two consecutive occurrences of the same extreme is 3 to 4 years. In a few weeks, the atmosphere adapts to changes in sea surface temperature. Contrarily, the ocean needs more than a year to adapt to the change in the wind field (https://www.morski.hr/video-sto-je-el-nino-a-sto-la-nina/). El Niño significantly affects the variations of the hydrological cycle, i.e. the planetary water resources manifested by the intensification of floods and droughts in various parts of the planet. The result is a decrease in agricultural output and an increase in economic and social instability, especially in developing countries (e.g., Meissner, 2002; Hund et al., 2021, etc.).

Impacts from meteoroids, comets, and asteroids have also caused sudden climate changes, and thus hydrological processes. The most famous of all asteroid impacts to the Earth (in the area of today's Yucatan Peninsula) happened about 66 million years ago. It is considered the main cause behind the disappearance of the dinosaurs. The impact caused tsunamis and huge fires that released so much sulfur into the atmosphere that it caused sudden and long-term climate change, specifically global cooling, often called nuclear winter.

There are not many published works (Lerman et al., 1967; Nesvetajlo, 1998) on how and to what extent the meteor air burst that occurred on 30 June 1908, known as the Tunguska event, in the Cheryabinsk area of Siberia, affected the climate and the hydrology of the larger region. Ol'khovatov (2003) states that there has been increased tectonic activity in the wider region and that, over a long period, the climate has worsened somewhat. A long period of good weather was almost instantly interrupted by sudden and intense precipitation accompanied by strong winds. Numerous strong thunderstorms appeared even in Europe, especially in the western part of Russia and Siberia. In the Perm region, more precipitation was measured than in any of the previous 70 years. The day before the impact (29 June 1908), the cloud cover at the nearest meteorological station Kezhma was 3. Immediately after the impact, it increased to a maximum value of 10, and a few days later, it was still higher than 7. As much as 200 km2 of terrain was devastated. However, this phenomenon, which happened merely 115 years ago indicates that such phenomena are still possible today. Earth’s atmosphere is bombarded by a million different pieces of space debris every day. Most of them are pieces of dust, but sometimes they are larger pieces. Also, in February 2013, at 9 hours and 20 minutes local time, a non-metallic meteorite with a diameter between 17 m and 20 m flew into the Earth's atmosphere over central Russia at a speed of about 64,800 km/h. It exploded over the Chelyabinsk region and injured more than 1,000 people.

Earthquakes can also significantly affect local and possibly regional variations of the hydrological cycle. These are natural disasters that very often cause landslides. Part of the soil on the slopes in labile equilibrium is set in motion by an earthquake. The moving soil mass often stops in the watercourse beds, preventing the existing flow regime. Such occurrences are relatively common, especially in Italy, China, Japan, the USA, Russia, etc. An example is the earthquake of magnitude 7.4 on the Richter scale in the Pamir Mountains that occurred in 1911. An amount of soil slid into the Murghab River (Tajikistan) and blocked the valley with an uncontrolled natural dam 567 m high. This earthquake created the Usoi Dam, the largest natural dam in the world, which formed Lake Sarez, which is still filling today. The lake is 55.8 km long and contains about 16 km3 of water. Although the dam poses a danger to the vast downstream area, the attempt to secure the dam and bring the reservoir to its purpose was abandoned due to the inaccessibility of the location.

An earthquake of magnitude 8.0 on the Richter scale that occurred in 2008 in the province of Sichuan (China) caused the occurrence of over 50,000 landslides, 256 of which ended up in watercourses blocking them and forming lakes. It is necessary to note that similar phenomena can be caused by lava emerging from a volcanic eruption and mudflows occurring after extreme precipitation (Roje-Bonacci, 2009; 2014). Earthquakes in karst terrain often cause the immediate formation of cracks along the surface and changes in the water circulation in the karst underground, causing the redirection of water flow on the surface and more often underground, where it cannot be easily controlled (Gosar and Brenčič, 2012). A local example in Slovenia occurred in the country’s northwest on 12 April 1998, with a magnitude of 5.7, which might have changed or opened new groundwater pathways through fractured dolomite layers in the slope, leading to the rainfall-triggered Stože debris slide in November 2000 (Mikoš et al., 2004). For example, it is asserted that the earthquakes that occurred in 2016 and 2017 in the central part of Italy caused the reactivation of a complex system of faults, the creation of new karst conduits, and the closure of existing ones, which completely changed the circulation of underground water within the karst aquifer (Di Matteo et al., 2020). Miyakoshi et al. (2020) described changes in the groundwater flow process caused by the 2016 Kumamoto earthquake, with a magnitude of 7.6 on the Richter scale.

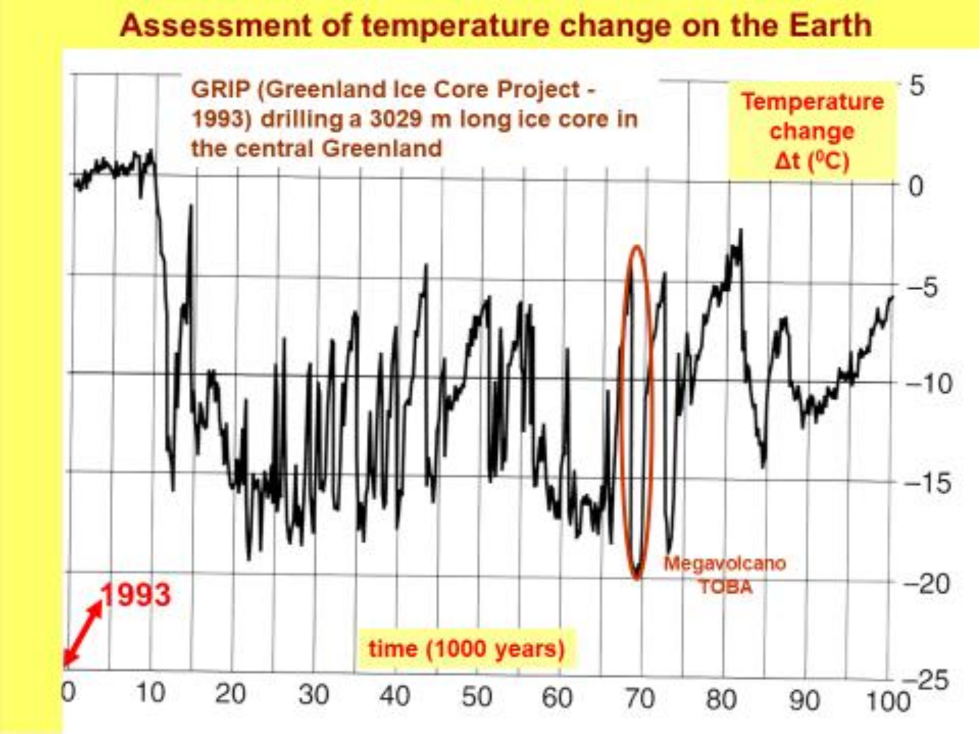

***Figure 1:** Time series of the Earth's temperature estimate starting in 1993, 100 thousand years ago. The graph is a result of the multinational project GRIP (Greenland Ice Core Project).*

***Slika 1:** Časovna vrsta ocene Zemljine temperature od leta 1993, 100.000 let nazaj. Graf je rezultat večnacionalnega projekta GRIP (Greenland Ice Core Project).*

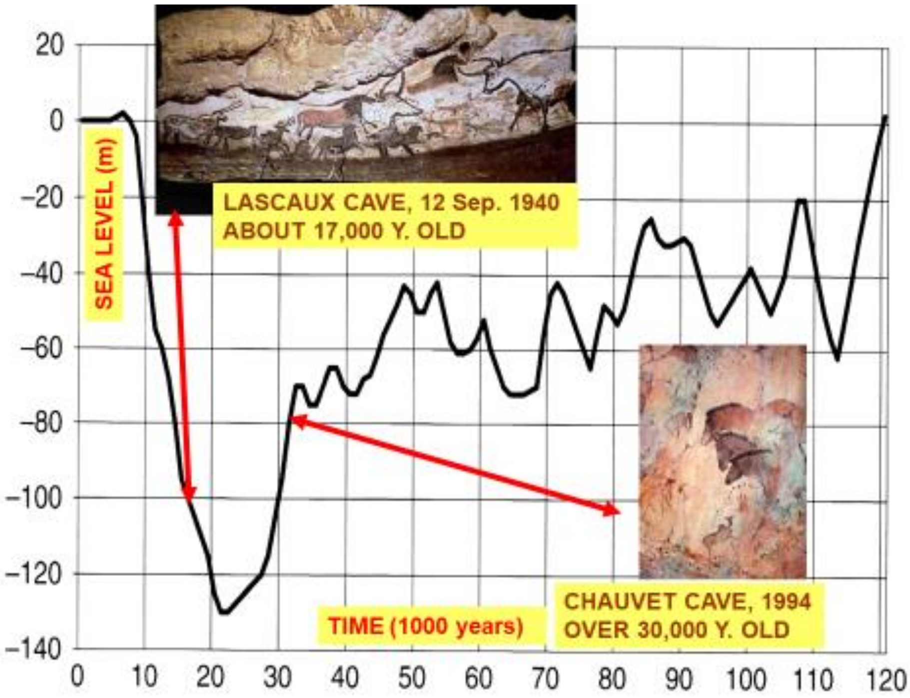

***Figure 2:** Time series of sea level in the previous 120,000 years (Clottes, 2001; Leroux, 2005; Lascanette et al. 2007).*

***Slika 2:** Časovna vrsta morske gladine v zadnjih 120.000 letih (Clottes, 2001; Leroux, 2005; Lascanette et al. 2007).*

3. Wolf's number and the Hurst phenomenon

The Sun is the Earth’s principal source of energy. In the attempt to explain the causes of climate change and the Sun’s role, Rind (2002) asks, *“Is the Sun the controller of climate changes, only the instigator of changes that are mostly forced by the system feedbacks, or simply a convenient scapegoat for climate variations lacking any other obvious cause? This question is addressed for suggested solar forcing mechanisms operating on time scales from billions of years to decades. Each mechanism fails to generate the expected climate response in important respects, although some relations are found. The magnitude of the system feedbacks or variability appears as large, or larger than that of the solar forcing, making the Sun’s true role ambiguous. As the Sun provides an explicit external forcing, a better understanding of its cause and effect in climate change could help us evaluate the importance of other climate forcings (such as past and future greenhouse gas changes). Whether the Sun acts as the controller of climate changes on various time scales, simply instigates the subsequent feedbacks that then dominate the observed record, or is only a convenient explanation for unobserved forcings or system oscillations, will probably be a matter of debate and continued investigation for many years. The answer may also bear on whether the continued growth of atmospheric trace gases will dominate the system response or whether it too will be swamped by the feedback, making predictions of any response equally difficult.”*

Since the Sun is an explicit external force, a better understanding of its effects on the planet’s climate, and consequently on other interactive processes in the system, is of utmost importance. From Rind's (2002) statements on climate change, the conclusion clearly emerges that many questions remain unanswered and that science must provide more reliable answers. One of the major drawbacks of the scientific explanation of this extremely topical issue lies in the fact that it is not possible to conduct real experiments on a global scale (Friis-Christensen and Lassen, 1991).

In this section, an attempt is made to indicate the possible important role of the relative Wolf number, W, in the variations of the hydrological cycle. The Sun’s activity is manifested in phenomena such as sunspots, solar flares, and coronal mass ejections (solar flares). Sunspots are associated with solar flares during solar maxima but can also appear during solar minima. These are areas where the strength of the sun’s magnetic field is thousands of times greater than the Earth's magnetic field. They become visible on the Sun's photosphere as a result of the intense magnetic flux pushed from deep inside the Sun. The Sun's core is heated to a temperature of 15.7 million K. A typical sunspot is made up of the penumbra, which forms the peripheral, brighter region, and the shadow, a dark, central region whose temperature ranges between 3500 K and 4000 K. Sunspot areas are 2500 K cooler than the rest of the Sun's surface. The solar cycle represents half of the 22-year magnetic cycle caused by the rotation of the Sun's magnetic fields.

Any solar activity can affect climate on Earth. In this sense, sunspots are of particular interest because they have been observed for over 600 years, so by comparing their time series, one can also judge their impact on certain phenomena observed on Earth ever since. The discovery of sunspots dates to the beginning of the 17th century as a direct result of having invented the telescope. In 1612, English astronomer Thomas Harriot was the first to observe sunspots with a telescope in 1610. Numerous works were written about them by Johanes Fabricius (1587-1616), Galileo Galilei (1564-1642), Thomas Harriot (1560-1621), and Christoph Scheiner (1573-1650). Sunspots have sparked fierce scientific debates.

Swiss astronomer and historian of astronomy Rudolf Wolf (1816-1893), professor of astronomy at the University of Zurich and director of the observatory in Berne, discovered, based on historical data recorded since 1610, the connection between sunspots and disturbances in the Earth's magnetic field. He published two papers on this matter in 1852 (Wolf, 1852. a; 1852. b). He introduced a quantitative description of the Sun's activity named Wolf's number of spots, W, after him. The time series of Wolf's number, W, corresponds to periodic (most often between 9.5 and 11 years) changes in the Sun's activity. It is defined by the expression:

$$W = k \times (10 \times g + s), \qquad (1)$$

where s represents the number of individual spots on the visible side of the Sun during the observation period, g is the number of groups of spots, while k represents a coefficient that depends on the sensitivity of the astronomical instrument and other observation conditions.

Figure 3 shows a time-series plot of the relative Wolf number, W (www.sidc.be/silso/yearlyssnplot). It changes periodically from 1700 to 2023. The mean annual values of sunspots up to 1748 are marked in black, while the average 13-month values, starting from 1749, are drawn in blue. The cyclical behavior of the values over an 11-year period is clearly visible.

The 11-year cycle is called the Schwabe cycle. In addition to the mentioned 11-year cycle, the amplitude of the relative Wolf number can also be observed. At the same time, the amplitude of the solar maximum changes over about an 87-year period. This cycle is called the Gleissberg cycle. The number of sunspots in the second half of the 17th century was extremely small, so that period was called the Maunder minimum. Historically, the timing of the Maunder Minimum coincides with the period of the Little Ice Age in Europe.

In addition to the Maunder minimum, a so-called Dalton minimum appeared at the beginning of the 19th century.

Sunspots occur during solar maxima. The solar wind blowing from the coronal cavities carries particles that travel to Earth and can cause damage through their radiation. Cosmic radiation is easily recognized as polar auroras appear. However, during solar minima, the Sun noticeably calms down, as proven by the lack of sunspots. The previous solar cycle, the 24th in a row, reached its solar minimum in December 2019, while its maximum was in April 2014, with a peak average of 82 sunspots.

To date, the issue of the relative Wolf number's influence on hydrological processes (primarily time series of mean annual flows) has been merely reflected in a small number of hydrologically oriented works. Therefore, the author stresses that the issue of the Sun's influence as expressed by the Wolf number on the hydrological cycle must still be given much greater attention. Solar activity was analyzed on a series of flows of the Nitra River (Slovakia) (Fendeková et al., 2014). Based on a series of 80 years (1931–2010), a clear 11-year cycle was found that coincides with the Wolf number cycle.

Climatic events throughout history, such as ice ages and warmer weather periods, correlate with periods of solar activity or with variations in total solar radiation. One of the most significant minima of solar activity was the Dalton minimum, which occurred in the periods 1790-1830 and 1796-1820, depending on the solar cycle they join (Komitov and Kaftan, 2004). In that period, below-average temperatures appeared in Great Britain. Neither the beginning nor the end of the Little Ice Age is precisely defined but it is considered to be the period between 1550 and 1880. This cooling period followed a warm weather period known as the Medieval Climatic Optimum. Within the Little Ice Age, there were three smaller cold periods beginning in 1650, around 1770, and 1850, with intervals of warmer weather between them. The Little Ice Age was characterized by extremely cold winters, primarily in Europe and North America. The expansion of the glaciers in the Swiss Alps in the middle of the 17th century destroyed settlements. The water in the Thames River and canals and waterways in the Netherlands froze in winter. During the winter of 1780, the entire New York harbor froze over. The frozen sea around Iceland extended for kilometers in all directions. The Arctic ice sheet expanded so much that the Eskimos could land in Scotland with their kayaks. Agricultural production was drastically reduced, the number of inhabitants in Iceland was halved, and the Viking colonies in Greenland disappeared.

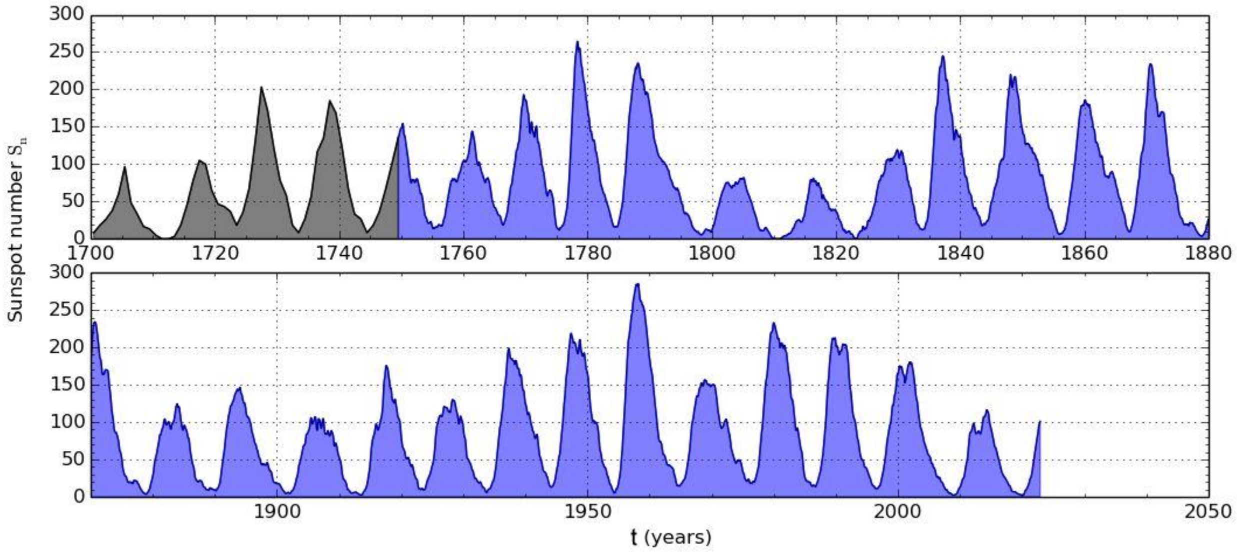

***Figure 3:** Time series of Wolf's number (number of Sunspots) in the period from 1700 to 2023 (www.sidc.be/silso/yearlyssnplot).*

***Slika 3:** Časovna vrsta Wolfovega relativnega števila (števila Sončevih peg) v obdobju od leta 1700 do leta 2023 (www.sidc.be/silso/yearlyssnplot).*

In his doctoral thesis entitled *The Influence of Solar Activity on the Earth's Space Environment and Climate*, Čalogović (2014) concludes that cosmic radiation does not globally affect cloud cover and therefore is not the cause of major climate changes and present-day global warming. The opposite conclusion was presented by Friis-Christensen and Lassen (1991); they believe that the length of the solar cycle as an indicator of solar activity is closely related to climate. A similar conclusion is reached by Kumar and Singh (2019). They emphasize that several studies indicate a strong correlation between solar variability and the temperature on the Earth's surface. These data suggest the effect of solar variability on the terrestrial climate at various time scales, from minutes to millions of years. Easterbrook (2016) published the second edition of the book in which he argued in detail the opposing theses on CO2 emissions being a primary source of global warming. Similar views were expressed in Solanki et al. (2013). They emphasized that the Sun's activities vary at all time scales, and the amplitudes of these variations depend on the wavelengths and time scale of duration. Although many aspects of these variations are well-defined, the exact extent of secular variations within the solar cycle and their spectral dependence are still debatable (Kopp et al., 2016; Aquila et al., 2016; https://www.climate.gov/news-features/climate-qa/couldnt-sun-be-cause-global-warming). The main driver of the sun's variability is magnetic phenomena on its surface. Solanki et al. (2013) believe that the global climate's response to these stimuli can be explained easily. Problems arise, though, in explaining regional climate reactions. When studying the influence of solar variability on the hydrological cycle at different scales of time and space, things become even more complex and unclear than when studying its influence on climate.

Throughout the entire history of the planet, the climate has changed irregularly at all time scales. Climate change is closely related to the Hurst phenomenon, whose existence has been detected in numerous hydroclimatic time series representing the stochastic equivalent of a simple scalar behavior of variables for a given time scale (Koutsoyiannis, 2003). Climate variability, whether caused by anthropogenic or natural factors, increases the uncertainty of hydrological processes. Koutsoyiannis (2003) showed that the traditional statistical approach to analyzing hydrological time series is not consistent with the climate's variable character.

Hydrological weather processes are driven by complex physical laws and mechanisms that are almost impossible to control. Addiction changes at different points in time. Dependence between observations can last for a long time, i.e. the past can have a long-term impact on the future in some processes. This is a phenomenon of long-term memory, whose existence was proposed by the hydrologist Hurst (1951), who noticed it while analyzing the hydrological sequence of the Nile River. He concluded that in many engineering problems, available time series data are not a reliable source for future behavior but represent only varying degrees of probability (Hurst, 1956). In simpler terms, some phenomena show characteristically strong dependence so that even their distant past is significantly related to their future. Today's understanding of the term "long-term dependence" is mainly based on the specific behavior of a random process's autocorrelation function (Grahovac and Grgić, 2019).

The time series is analyzed of inflows of various time increments (day, month, year) on a specific watercourse profile, Q_i, with $I \in (1, 2, ..., n)$. Hurst (1951, 1956) and Hurst et al. (1965) studied the range of the cumulative deviations of inflow at a given time from the average inflow. Through a detailed investigation of the range's property, they concluded that the scaled range, R/σ (where σ represents the standard deviation of the series), increases with the length of the series, n. The difference between the flow, Q_i, and the average flow, Q_{av}, at the moment i, ΔQ_i, i.e. at the end of each period i, is:

$$S_i = \Delta Q_i = Q_i - Q_{av}, \tag{2}$$

The expression, depending on the sign, describes the filling or emptying of the reservoir. After period i, the successive sum of cumulative deviations is calculated with the expression:

$$\Sigma S_i = \Delta Q_1 + \Delta Q_2 + \ldots + \Delta Q_i = \Sigma \Delta Q_i\,, \tag{3}$$

The maximum value is called the maximum excess or maximum of partial sum deviation and is marked $Sn+$. The minimum is called the minimum deficit or the minimum of partial sum deviation and is marked $Sn-$. The range, R, is calculated as the sum of these two values:

$$R = S_n^{+} + |S_n^{-}|, \tag{4}$$

The range, R, represents the size of the reservoir required to maintain the outflow Q_{av} (the average value of all inflows) if the inflows are equal to Q_i.

According to that study, the natural phenomenon and the length of the series are given by the empirical relation:

$$R/\sigma=(n/2)^{H}, \tag{5}$$

where H is the Hurst coefficient with an average value of 0.73 and a standard deviation of 0.09. These values were calculated based on the analysis of 75 phenomena and 690 data sets. If the series follows a normal distribution and if the members are independent, for high values, n, the following applies:

$$\mathrm{R}/\sigma=(\mathrm{c} \times \mathrm{n})^{0.5}, \tag{6}$$

The Hurst phenomenon occurs when the value of H exceeds 0.5. Hurst exponent values between 0.5 and 1.0 are indicators that the analyzed time series exhibit stable behavior. The higher the value of H, the more significant the trend.

4. Anthropogenic influence on variations of the hydrological regime

The UN predicts that by 2050, almost 6 billion inhabitants of the planet will suffer from clean water scarcity (Boretti and Rosa, 2019). Increased needs for water, reduced water resources, and increased pollution result from a dramatic increase in the population and in economic growth, along with the effects of other natural and anthropogenic activities. Variations in hydrological processes have a direct cause-and-effect relationship with the intensification of the UN's worrying forecasts presented earlier. Intensive research during recent decades has concluded that the pressures on the hydrological cycle are the greatest in the Anthropocene period and on almost all spatial and temporal scales. To be able to oppose these worrisome processes as successfully as possible, it is first of all necessary to study in detail and reliably determine the true causes that drive the negative processes related to the hydrological cycle.

When managing water resources, especially distributing water to users, it is important to know the current availability of water. Decisions from the past will affect those in the future. The accelerated use and consumption of water resources in the near future will require the development of a long-term strategy for their use (Berbić, 2017). A hydrological process's structure provides important information about its temporal regularity. Long-term changes in the structure of hydrological processes are a significant issue not only of modern science but perhaps even more of engineering, which plays a key role in achieving realistic and effective goals. The structure of the hydrological process is an important property based on which information is obtained about its temporal regularity. Long-term changes in the structure of the hydrological process are a significant issue, essential for the efficient use of water resources that modern science has to deal with.

Dams and reservoirs are the most common engineering creations that have had the strongest impact on changing the hydrological regime not only of the watercourse on which they were built but also of the entire basin and the wider region. They were mainly built to level the hydrological regime to enable safe agriculture, protect against floods, generate electricity, etc. In the beginning, they served these functions well, but as time passed, unexpected negative consequences caused by their functioning became more numerous and more drastic. At the beginning and in the middle of the 20th century, many dams were built all over the world. From the middle of the 20th century, resulting from all the negative effects observed, there was a sharp decline in the construction of dams. At the beginning of the 21st century, there is even greater need to provide water for agriculture and citizens during dry periods, to protect against floods, and to generate hydroelectric power. Since no satisfactory substitute for dams and artificial reservoirs has been found, their construction has again increased. As interest in the construction of dams grew anew, it caused heated debates about how useful dams and reservoirs are and how much damage they cause. (Hudek et al., 2020).

The essential dilemmas about the positive and negative consequences of dams and artificial reservoirs were considered by Biswas (2004), who tried to answer whether dams are a panacea for all problems or whether they inherently cause disasters. The literature contains very different treatments of the role and consequences of dams and reservoirs. Muller (2019) believes dams and their reservoirs can mitigate local and regional climate changes. Berga (2016) advocates for the construction of dams, stressing that hydroelectric power is a clean, renewable, and environmentally friendly source of energy. According to him, hydroelectric power and climate change have an interactive relationship since hydroelectric power significantly contributes to the reduction of greenhouse gas emissions and thus helps mitigate global warming. At the same time, mitigating the intensity of the increase in air temperature affects the greater availability of water resources and, thus, the security of the supply of electricity and water for irrigation. Contrary opinions are given by other authors, such as Yaggi (2021), who claims that hydroelectric power plants are not a solution to mitigating the climate crisis, noting that artificial hydropower reservoirs create significant amounts of methane, which drives global warming 86 times more strongly than CO_2. Of the greenhouse gases emitted from artificial reservoirs, 80% is methane. Ocko and Hamburg (2019) state that dams and their reservoirs produce methane, released due to microbes feeding on vegetation submerged by the artificial reservoir. Methane production in reservoirs increases significantly because of sediment retention. Artificial reservoirs of hydroelectric power plants after their first years of construction can cause stronger warming than coal-fired power plants, according to Maeck et al. (2013).

Dams and reservoirs cause a sudden change in natural (climatic, biological, sociological, etc.) processes downstream, but also upstream on the watercourse and in the wider surrounding area. Downstream, there is a drastic reduction in the transport of all types of sediment, nutrients, seeds, and biological substances, and prevention of fish migration. Reservoirs, depending on their properties (primarily the volume of water and the depth of the water in it) as well as the way of management, affect the hydrological and biological regime, but also the water temperature and the local or regional climate (e.g., Bonacci and Oskoruš, 2010; Horvat et al., 2006; Webb and Nobilis, 2007; Dai et al., 2011; Palmeirim et al., 2014; Bonacci et al. 2022; Jánosi et al., 2023, etc.). It is a practically inexhaustible topic where each case is different.

In addition to dams and reservoirs, variations in the hydrological regime are affected by other human interventions. Firstly, this refers to the change of land use from natural to agricultural or urbanized. Such activities strongly and directly affect the change in water balance components. The consequences are more strongly manifested in changes in evapotranspiration and groundwater recharge.

5. Final considerations

The climate is not a steady-state process and is obviously continuously changing, causing significant variations in the local, regional, and eventually global hydrological cycle. Besides the climate, the hydrological cycle is affected by other natural and human-caused processes that may happen simultaneously, last for different periods, and occupy various spaces with different environments that react significantly differently to these stimuli. Because of this, it is very difficult to assess with scientific certainty which process is dominant and how it will unfold in the future. In the attempt to answer this question, the paper points to various possible natural and anthropogenic mechanisms that affect the hydrological cycle on different time scales ranging from just a few moments to millions of years.

Water represents a natural resource without which any life on the planet could not be possible. Man is by far the biggest consumer of water. For basic physiological needs, we consume from 2 l/day to 3 l/day, which means that 10 km^3 to 15 km^3 of fresh water is consumed daily just for the basic needs of people on Earth. According to World Health Organization standards, sanitation requires an average of 150 l/resident per day is needed, which amounts globally to about 750 km^3 of water per day.

In this paper, we wanted to point out the neglected role of the Wolff number in hydrological analyses and the controversies related to the impact of natural and anthropogenic factors on hydrological processes at global, regional, and local scales over various time increments.

The author is aware that it is not possible to give definitive and reliable answers to the treated problem and that it is necessary to invest a lot more effort and resources to get at least somewhat closer to the solutions. Yet, it is crucial to find these solutions to ensure sustainable development, which crucially depends on the availability of water resources, that is, on the hydrological cycle. It is obvious that some factors act simultaneously and others at different time increments, some cause immediate and short-term consequences in the hydrological cycle, and, for others, consequences appear only after a long time, sometimes manifesting on a global scale and sometimes affecting only the regional and/or local hydrological system.

When analyzing the influence of various factors on the hydrological cycle, it is necessary to consider the spatial and temporal diversity of water occurrence, i.e., the different manifestations of the hydrological cycle in various environments. Solving these problems is impossible without a range of experts who, with their comprehensive knowledge and efforts, can understand complex, interrelated issues and then come to reliable conclusions. Narrow specialization and a definite preference for only one aspect without considering other possible causes cannot completely illustrate the problem analyzed here. Unfortunately, today the preferred hypothesis is that climate change caused by anthropogenic emission of greenhouse gases, mainly CO_2, is responsible for all or at least most of the global causes related to variations in the hydrological cycle. Of course, this does not mean that the author denies this hypothesis but only believes that other possible factors should be included in the consideration simultaneously, some of which are acknowledged in this paper.

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