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Original scientific paper

DETECTION OF CLIMATIC FLUCTUATIONS BY HILBERT-HUANG METHOD IN THE DATA OF ZAGREB-GRIČ CENTENNIAL OBSERVATORY, CROATIA

Detekcija klimatskih kolebanja Hilbert-Huangovom metodom na podacima stoljetnog opservatorija Zagreb-Grič, Hrvatska

ANA PETROV[1] and BRANKO GRISOGONO[2]

[1]Technical school Šibenik,
Ante Šupuka 31, 22000 Šibenik, Croatia
[2]Department of Geophysics, Faculty of Science, University of Zagreb,
Horvatovac 95, 10000 Zagreb, Croatia
ana.petrov@skole.hr

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Abstract: Advanced statistical methods are applied on long-term data sets from Zagreb-Grič centennial observatory in Croatia to address recent climate change and variabilities; annual averages are used. Hilbert-Huang transform (HHT), consisting of empirical mode decomposition (EMD) and Hilbert spectral analysis (HSA), is an empirically based data-analysis method for extracting periodic components embedded within generally nonlinear and non-stationary data. The EMD splits the original series into a so-called intrinsic mode functions (IMFs). First, using the EMD algorithm, intrinsic mode functions (IMFs) are obtained. The analysis of low frequency IMFs indicates significant influence of the North-Atlantic Oscillation on the air temperature, cloudiness and precipitation series in the part of northern Croatia. For the considered climatic elements, the analysis revealed mild deviations in natural fluctuations of the analyzed signal for the last 30 to 40 years, which are most likely caused by anthropogenic activities.
Next, HSA is applied to each IMF obtained for the series of annual averages of sea level air pressure. In order to validate this approach and the results, an associated Hilbert spectrum (HS) is compared with the continuous wavelet analysis, i.e., this is another corresponding checkup. The comparison shows significantly improved time and frequency resolution in favor of HS. Moreover, HS provides a unique capability of displaying intra-wave frequency modulation, i.e., changes in frequency that occur within one cycle of oscillation.

Key words: empirical mode decomposition, intrinsic mode functions, Hilbert transform, climatological series, climatic fluctuations, Zagreb-Grič

Sažetak: Napredne statističke metode primijenjene su na srednje godišnje podatke s opservatorija Zagreb-Grič. Prema Svjetskoj meteorološkoj organizaciji (2018) to su najstariji neprekinuti klimatološki podaci u Hrvatskoj. Cilj je uputiti na aktualne klimatske promjene te pripadnu varijabilnost. Primijenjena je Hilbert-Huangova transformacija (HHT), koja sadržava empiričku dekompoziciju modova (EMD), te Hilbertova spektralna analiza (HSA), koja iz početno nelinearnih i nestacionarnih podataka može izdvojiti periodičke komponente. Pritom se EMD svodi na tzv. intrinzične (bazične) modove (IMFs). Analiza upućuje na značajan utjecaj Sjeverno-atlantske oscilacije (NAO) kroz niskofrekventne IMF-ove: na temperaturu zraka, naoblaku i oborinu u tom dijelu Hrvatske. Uočeno je određeno odstupanje od prirodnih varijacija tijekom posljednjih 30-40 godina, što je najvjerojatnije posljedica aktualnih klimatskih promjena.
Nadalje, primijenjena je HSA na sve komponente IMF-a odgovarajućeg dugogodišnjeg niza

tlaka zraka. Za daljnju usporedbu i provjeru rezultata pridruženi Hilbertov spektar (HS) uspoređen je s metodom valića. Usporedba upućuje na značajne prednosti HS-a; uključuje mogućnost HS-a da prikaže međuvalnu modulaciju frekvencije, tj. promjenu frekvencije unutar jedne osilacije.

Ključne riječi: metoda empirijskog rastavljanja, prirodne rastavne funkcije, Hilbertova transformacija, klimatološki nizovi, klimatska kolebanja, Zagreb-Grič

1. INTRODUCTION

Continuous long-term time series data are the core of climatology and one of the essential components for understanding recent climate changes. In order to analyze such series, it is important to use advanced techniques suitable for nonlinear and nonstationary data series. Fourier transform's incapability to cope with nonstationary and nonlinear phenomena has proven to be sometimes problematic (e.g., Priestley, 1988; Stull, 1988). Namely, data collected from the real world are mostly not periodic and they often seemingly randomly change in time and space as a result of many, mostly nonlinear, processes. Linear methods used to describe such data are not ideal, and difficulties that arise when such methods are used are numerous. Hilbert-Huang transform (HHT) is an adaptive and effective tool developed to cross the borders of such limitations (Huang et al., 1998; 1999; 2003). It consists of two parts. The first one, being the key part, is an Empirical Mode Decomposition (EMD), the method that locally and automatically splits the original signal into so-called Intrinsic Mode Functions (IMFs), without leaving a time domain. Here, IMFs are the basic, essential functions of which the signal is composed and can provide insigt into various signals contained within the data. They are not set analitically but are determined instead by an analyzed sequence alone, i.e., data controlled. Only when one has obtained such fundamental functions, we can apply Hilbert Spectral Analysis (HSA), the second part of the method. It is used to calculate instantaneous frequences of each IMF, as functions of time. Since IMFs are all in the time-domain and of the same length as the original signal, varying frequency in time can be preserved; this is a key point. Remaining in the domain is important since natural processes often have multiple causes, and each of these causes may happen at specific time intervals. The approach of the HHT method is unique and quite different from others, perhaps more recognised, methods for data analysis, and enables physically more meaningful time-frequency-energy representation of time series. In this paper, the method is applied to time series of annual averages of air temperature, cloudiness, air pressure and annual sums of precipitation observed in the period 1862–2015 at the observatory Zagreb-Grič, Croatia, a centennial observation station recognized by the World Meteorological Organization (WMO, 2018). This implies high quality of the data observed without ever moving the station. More about that can be found e.g., in the book by the Faculty of Science (Orlić et al., 2011). The related seasonal data are analyzed via the same methods applied in this study in Petrov (2016); however, that is not included in this study for brevity and conciseness. The same data series are often used in studying the climate of the area, e.g., for assessing drought effects on agriculture (Pandžić et al, 2020). In some previous studies of these climatological series, linear analyses have been used; although useful and giving certain insight, such methods are not completely appropriate for unsteady nonlinear time series. For example, Gajić-Čapka (1993) used linear regression to estimate the related trends; Šinik (1985) used the moving average for revealing long-term variations; Radić et al. (2004) used EMD on that time series up to the year 2002 and indicated offprints of the Atmospheric General Circulation (AGC) in the data, i.e., they confirmed overall flow regimes at these latitudes. Here, we foster and advance those analyses; we add a value by deploying the same and additional methods for the data scrutiny and extent the time series by 13 years, i.e., by about 9%. This hints at the aim of our study. Almost needless to say, regional climates become progressively more the research focus, and the related type of modeling (e.g., Güttler et al., 2014) is exceedingly dependent on such secular climate time series, their reproduction, evaluation and more, as deployed here. Some studies, using the same source as here, deal with urban heat islands (Ogrin, 2015), but that is not the aim of our study.

Motivation for such an approach is a general and professional interest for climate changes during the several last decades. Since efficiency of HHT analysis has been demonstrated many times in the field of biomedicine, engineering, finances and geophysics (Huang et al., 1999), and previous studies have shown results with more values than any traditional method (Huang et al., 2003), its application could contribute to better understanding of cases of recent climate fluctuations at the broader area of Zagreb, that is representative for the NW continental part of Croatia (e.g., Gajić-Čapka, 1993; Pandžić et al., 2020). Even though HHT has so far been proven to be very effective, the technique itself has still not been fully defined theoretically (Huang et al., 1998). The goal of this work, besides the already mentioned analysis of annual sums and averages, is to also contribute experimentally towards a better understanding of the method itself. Of course, one humbly wants to extend necessary work of the other authors, and especially so to contribute to Radić et al. (2004) in this context.

2. MATERIAL AND METHODS

The HHT method was originally formed in 1995 and was named Empirical mode decomposition and Hilbert spectral analysis (EMD-HSA), see e.g., Huang et al. (1998; 1999). As already mentioned, the method consists of two parts: the first EMD part decomposes the signal into so-called IMFs, while the second part, Hilbert transform, is applied on such functions. Locality and globality are key issues there (e.g., Akima, 1970). Each IMF represents simple harmonic functions whose amplitudes and frequencies are functions of time and are defined as 1) functions which have the same number of zero crossings and extremes or can differ at most by one, and 2) the mean value of the envelope defined by the local maxima and the local minima is zero.

An algorithm used to calculate IMF is called the sifting process and is described as follows:
1. for data $x(t)$ identify local maxima and local minima and interpolate the extrema to obtain upper and lower envelopes,
2. calculate the mean of the two envelopes, m_1. For the interpolation between local minima (maxima), the Akima cubic spline is used (Akima, 1970). This kind of interpolation avoids wiggling, which is common to many interpolation methods, thus resulting here with smoother results.
3. obtain the difference between the data $x(t)$ and the mean $m_1(t)$, $h_{11}=x(t) - m_1(t)$. $h_{11}(t)$, which is an approximation of the first IMF, is treated as a new signal. In case that the above mentioned mandatory conditions are not obtained once the first iteration is completed, the sifting process is repeated a number of times until the number of zero-crossing of h_{1k} equals the number of extrema (±one) und until the symmetry around local zero mean is obtained. For the interpolation between local minima (maxima), in step 2, the cubic spline of Akima is used (Akima, 1970).

The question arises, when to end the sifting process? Huang et al. (2005) suggested the ending of it once the mandatory conditions are obtained for at least three iterations in a row. Once all those conditions are satisfied, h_{1k} is called the first IMF, being labelled as IMF_1 should contain the finest scale in the oscillations of the shortest period, i.e., it must represent the finest scale or the shortest period component of the signal. IMF_1 is then separated from the rest of the data by $r_1 = x(t) - IMF_1$, and the first residue is obtained and further analyzed by the same procedure. Steps 1 to 3 are repeated in order to estimate IMF_2 and r_2, and so on. The process is repeated until IMF_n or residue r_n become monotonic functions. In the end, a given signal $x(t)$ can be written as:

$$x(t) = \sum_{j=1}^{n} IMF_j + r_n \tag{1}$$

Expression (1) shows that EMD is actually a signal-dependent filter, which extracts oscillations with the highest frequency from the given signal.

This method starts from a simple assumption that most natural signals are composed of many superimposed, coexisting, simple oscillatory modes (e.g., Priestley, 1988; Huang et al., 1999). That is understandable since measured sets of data are very often the result of many different physical causes which occur in different yet connected time intervals (e.g., Lovejoy, 2019). The basic idea is that after the decomposition, each IMF should represent one of those modes, and thus it would be much easier to find the related physical cause.

Another advantage of such an approach is that through the sifting process it is possible to locally remove high frequency components with more precision and accuracy than we use e.g., low pass filter. Namely, the sifting process will not cause smoothing and shortening of the data length (Huang et al., 1999; 2003). Furthermore, such filters are mostly linear. In case that the filtered signal is a result of nonlinear processes, classical filters can only pick up or leave out harmonics (Priestly, 1988; Huang et al., 1998).

Only once the IMFs are obtained, the Hilbert transform can be applied to each IMF component in order to compute the instantaneous frequencies.

Aside from all the obvious advantages, EMD method also has some limitations. Though it successfully separates simple oscillatory modes of different frequencies, Wu and Huang (2004) showed that EMD is a binary filter that is capable of sifting only periodical components that differ by a factor of two. In cases that a signal has two or more superimposed periodical components whose periods differ for less than a factor two, IMFs obtained in that way will be the superposition of all the components embedded within that binary range.

3. RESULTS AND DISCUSSION

Here, each climatic element is analyzed using the EMD method and is afterwards discussed. The goal is to find and analyze (to a certain degree) physical causes of fluctuations of climate elements measures in Zagreb, which is representative for the NW continental part of Croatia. To achieve low frequency, variations on decadal and centennial scale will be observed. Since our focus is on relatively low frequency variations, IMF1 and IMF2, containing high frequency scale will not be included in the analysis.

Aside from observing individual components, sums of IMFs will also be addressed. For the simplicity, IMFs are renamed, last IMF becomes k_1, second to the last k_2, etc.

In order to detect and understand physical causes of variations of climate elements, the influence of AGC is considered, and, of course, observed (e.g., Holton, 1992). In midlatitudes, AGC has a form of western current and it is in labile balance between the Hadley zonal and Rossby wave regime. Radić et al. (2004) indicated that the Rossby regime prevailed over the Hadley regime after 1930. Exchange of those two models is possible to track through North Atlantic Oscillation (NAO) index. Note that NAO is measure of the strength of the western flow blowing over the North Atlantic ocean in the latitudes between 40°N and 60°N and, as such, it is the most important mode of the atmospheric variability above most of Europe (Wallace and Gutzler, 1981; Hurrell et al., 2003).

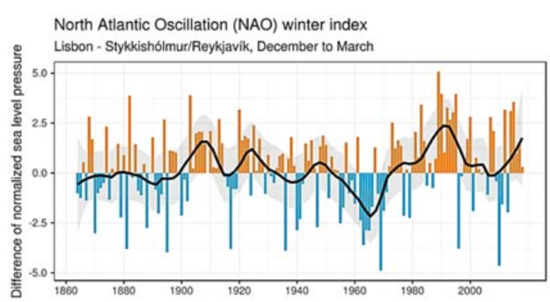

Figure 1. NAO Index Data, Climate Analysis Section, NCAR, Boulder, USA, after Hurrell et al., (2003).

Slika 1. NAO indeks, Climate Analysis Section, NCAR, Boulder, USA, Hurrell i sur. (2003).

Figure 1 shows the distribution of the NAO winter index in the period between 1862 and 2015. Although explicit periodicity when observing exchanges between positive and negative phases cannot be clearly observed, it is possible to sign out longer periods when the index was in mostly positive (1900–1940 and 1970–2015 and longer) and mostly negative (1862–1900 and 1940–1970) mode.

3.1. Air temperature

Using the EMD method on the series of annual air temperature averages at the observatory of Zagreb-Grič, seven IMFs and the residue were obtained, as shown in Figure 2. Further details on the decomposition are in Figure 3. The NAO influence can be seen if IMF3 is considered in Figure 2d. Namely, the positive NAO phase is connected with the above average air temperatures and weaker moisture inflow from the Atlantic Ocean (Hurrel and Van Loom, 1997). Warmer and drier conditions will result in generally more stable weather. In contrast, during the negative NAO phase, because of the inflow of the moist and colder air, weather conditions are, on average, more unstable; IMF3 shows that by vibrating in higher amplitudes during mostly negative phase and vibrating in lower amplitudes during mostly positive phase. The same fact can be seen in IMF2 and IMF4, but to a somewhat smaller degree. In Figure 2h, IMF7 isolates from the original data sets and the frequency of the exchange of the NAO phases nicely, so it can be inferred that IMF7 represents the influence of the NAO on the air temperature. During the positive NAO phase, the IMF expectedly shows higher air temperature, while during the negative phase the related

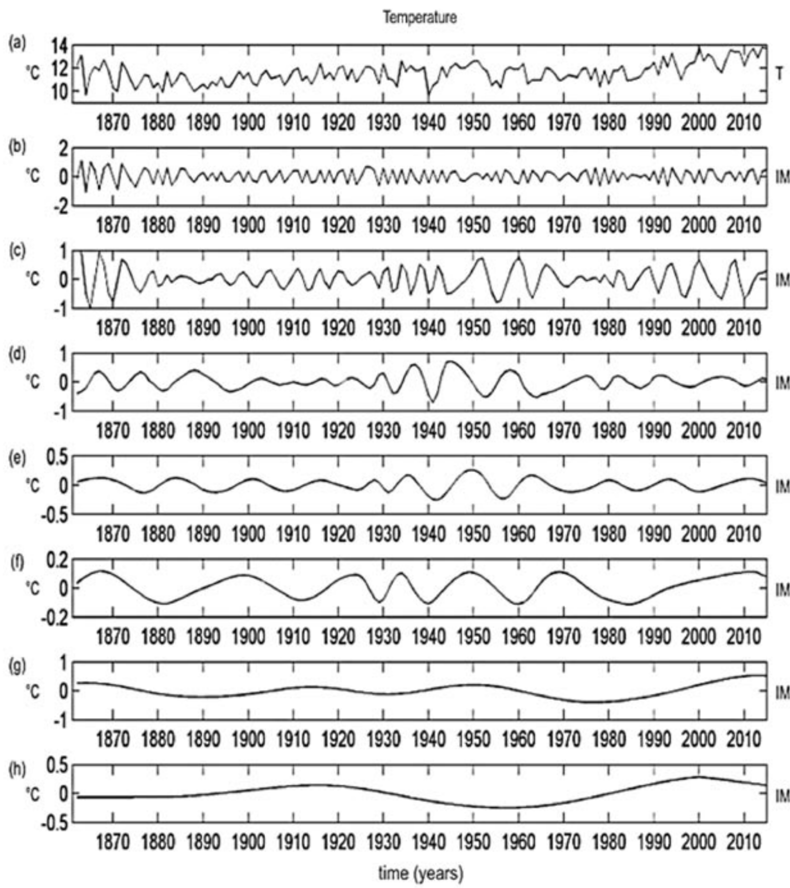

Figure 2. Data series of annual air temperature averages, Zagreb-Grič observatory (Zagreb, Croatia), and its decomposition into IMFs. The original data are at the top, (a) and the consecutive IMF-s follow as (b) through (h), see the text for details.

Slika 2. Vremenski niz godišnjih srednjaka temperature zraka, opservatorij Zagreb-Grič te rastav na pripadne IMF-ove. Originalni su podaci na vrhu, (a), potom slijede IMF-ovi od (b) do (h). Vidi tekst za detaljnije objašnjenje.

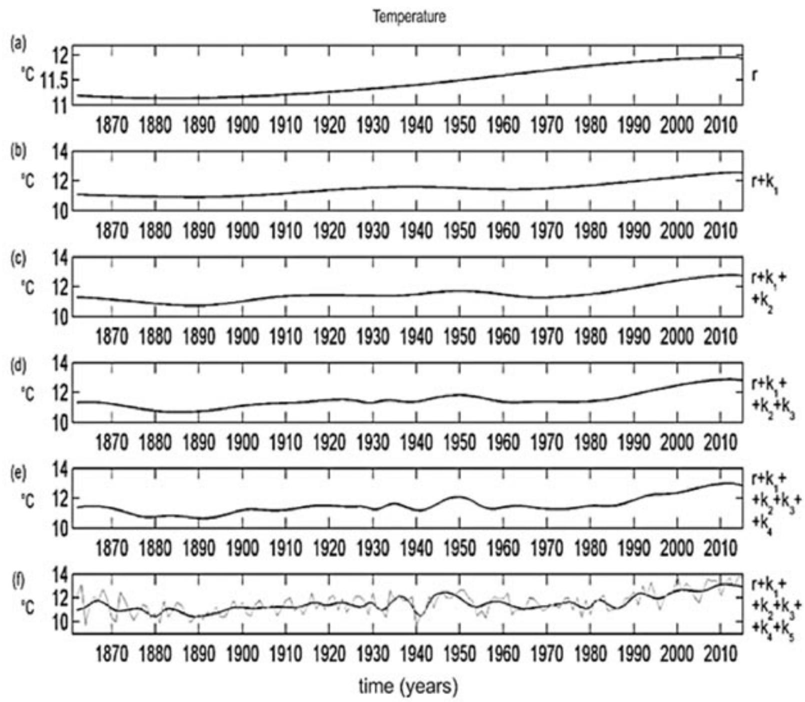

Figure 3. Cumulative sums of IMFs for annual air temperature data, starting from a) the residue (*r*), b) through f) (black) backward (k_1 is the last i.e., the lowest frequency IMF, k_2 is the second to the last IMF and so on). The first two (i.e., the highest frequency) IMFs are excluded from the sums. The original data, Zagreb-Grič observatory is shown at the bottom, f), using the light grey curve.

Slika 3. Kumulativne sume IMF-ova vremenskog niza godišnjih srednjaka temperature zraka počevši od a) reziduuma (*r*), od b) do f) (crna boja) unatrag (k_1 je zadnja, tj. IMF ima najniže frekvencije, k_2 je predzadnja itd.). Prve dvije (tj. IMF-ovi najviših frekvencija) izuzete su iz suma. Originalni podaci s opservatorija Zagreb-Grič prikazani su na dnu tablice f) svijetlosivom krivuljom.

air temperature is lower. During the last three decades, the values of the NAO index are extremely high, and in the same period the amplitude of IMF7 is the highest – in accordance with NAO. By now, it should be clear that our analysis largely confirms the existing findings about AGC over the area (Rossby and Hadley regimes, and more; see e.g., Radić et al., 2004). We complement the previous studies, especially about NAO effects over the area considered while the data series are extended here; furthermore, a comparison with another method will be provided, too.

Residuum and superposition of the IMFs are shown in Figure 3. The residuum corresponds to an upward trend of the annual air temperature averages that started in the beginning of the 20th century and continued until today. If IMF7 is superimposed on that trend, we obtain the curve $r+k_1$, (Fig. 3b). The fact that global warming has accelerated in the last ≈ 30 years can be seen in Figure 3b. Aside from that, air temperatures on that curve do not reach 13°C, while the annual air temperature averages of the original data those years reach 13.8°C. It can be concluded that the NAO phenomenon is insufficient itself to explain the warming we are witnessing in the past several decades. Namely, it is evident that additional factors exist for the cause of the air temperature rise in the period after about 1980. By observing Figures 3b–3f, one can see that the air temperature values additionally increase as more *k* components are added, one by one. This leads to a conclusion that the factor causing it is not periodic, so its influence is not seen in one, but is instead present in almost every IMF. All that suggests two causes for the air temperature increase at Zagreb-Grič observatory: primarily a warming climate and secondarily, an urban heat-island effect imbedded (e.g., Ogrin, 2015), as the city of Zagreb has been grown gradually (very little within a radius of about 1 km during the last several decades).

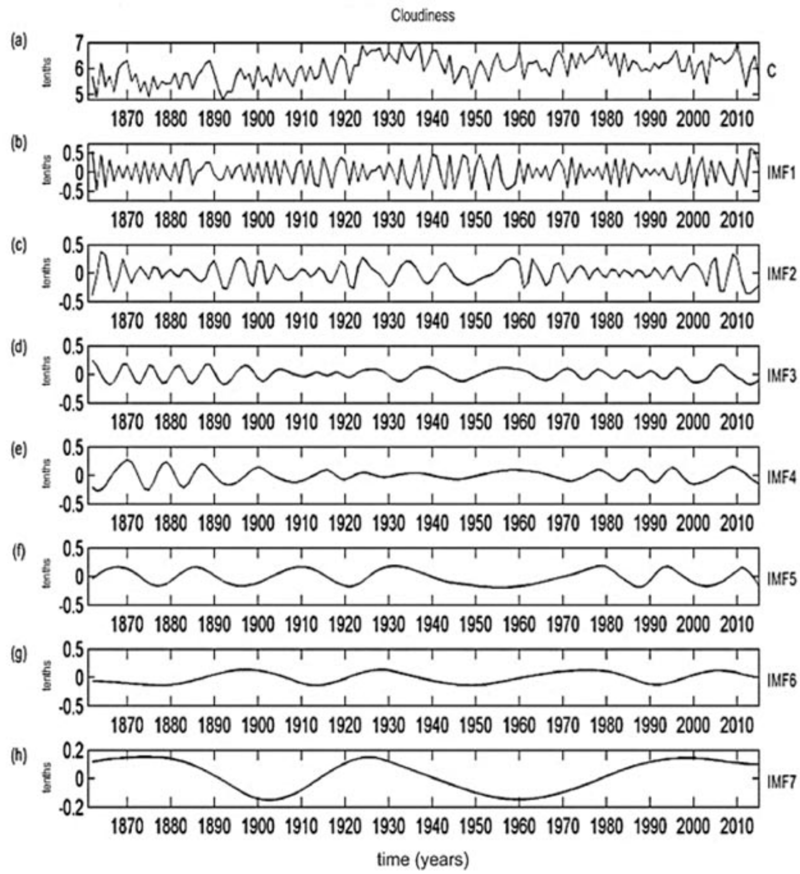

Figure 4. Data series of annual cloudiness averages and its decomposition into IMFs, Zagreb-Grič observatory.

Slika 4. Vremenski niz godišnjih srednjaka naoblake i pripadni rastav na IMF-ove, opservatorij Zagreb-Grič.

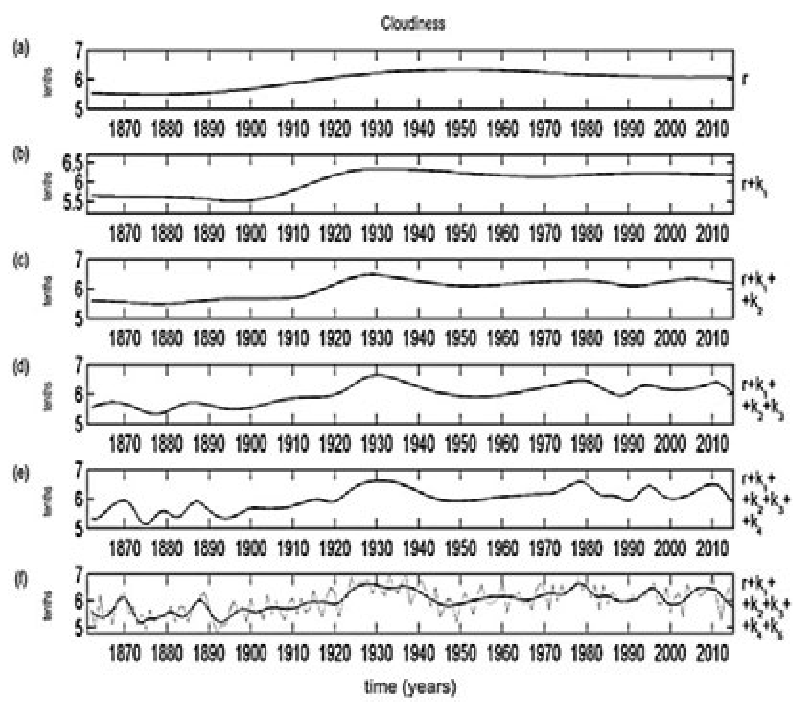

Figure 5. Same as in Figure 3, but for cloudiness.

Slika 5. Isto kao slika 3 samo za naoblaku.

3.2. Cloudiness

Using the EMD method on the series of annual averages of the cloudiness at Zagreb-Grič observatory, seven IMFs and residuum were obtained for this analysis, as shown in Figure 4.

The residuum in Figure 5 shows an increasing trend of cloudiness at the beginning of the 20th century and a mild decrease in the last 30 years. There had most likely been an increase in air pollution at the beginning of the 20th century, caused by fossil fuel combustion and industrialization; namely in a polluted atmosphere, aerosol content is increased (e.g., IPCC, 2021; Gašparac et al., 2020). Aerosol is known as condensation nuclei, upon which water vapor condensation begins in the atmosphere. Since the early 1980s until today, because of the use of higher quality of fuel and better control of the industrial and traffic pollution, and thanks to the increase in ecological consciousness on a global level, the atmospheric pollution is becoming generally reduced in Europe, which has resulted in decrease of foggy and cloudy days, that is mildly seen in the residue (Fig. 5a). This mild decrease in the cloudiness during the last 30–40 years is likely related to the precipitation decrease, which is an important point, as also found in another independent study of Pandžić et al. (2020). Aside from that, the influence of NAO is discussed again. Figure 4h shows IMF7 which vibrates in a similar period as exchange of the positive and negative phase of the NAO index. However, this match in the case of cloudiness is not so clear, like in the previous case of air temperature. The cause for it can be inferred if seasonal averages, and their decomposition is examined (checked yet not shown here for brevity, for details see Petrov, 2016). The mode IMF7 of the winter season shows clear correlation with NAO. Namely, in other seasons the NAO influence is reduced so other factors come to the fore. Satoh et al. (2012), using a global non-hydrostatic model of the atmosphere, studied changes that form in total cloudiness in regard to the rise in air temperature values. Those numerical simulations showed that an increase and prevalence of high cloudiness occurs because higher air temperatures increase evaporation from water surfaces, which will also contribute to the total cloudiness increase during warmer conditions. So, in this case, increase/decrease in air temperature will result in increased/reduced total cloud cover. It is probable that this case will prevail only when NAO influence is reduced, i.e., in spring, summer and fall season.

3.3. Precipitation

Using the EMD method on the series of annual sums of the precipitation, seven IMFs and residuum were obtained, as shown in Figure 6. Further details on the related decomposition are in Figure 7.

The NAO influence can be detected in IMF7, shown in Figure 6h. Positive NAO index is connected with reduced precipitation amounts in Zagreb area (Stilinović et al., 2014). IMF7 captures the period of NAO index exchange, and correlates negatively with it. The residue (Fig. 7a) shows a trend of reduction of total precipitation amount in the past ≈ 100 years or so; this has been accentuated after ≈ 1920–30. This is in accordance with the fact that in that period NAO was mostly in its positive mode. However, the trend of precipitation decrease in the last thirty years is somewhat relaxed (yet in its minimum), probably due to occasional but more intense precipitation events (not seen very clearly in the yearly data deployed here, though, found in the daily data and observation diaries). The analysis similar to the one done with the air temperature data will show a relative increase of the precipitation amount in that period while adding k components (i.e., higher modes), one by one, which can be seen in Figures 7d to 7f. Like it was the case with air temperatures, this factor is interpreted as a footprint of the recent global warming. As a side note, most climate models predict 1 to 3% of global increase of precipitation amount per degree of warming; hence, where regular precipitation patterns of moderate intensity exist, as around the area of Zagreb, the higher modes suggest this relative precipitation increase that is superimposed on the overall negative trend of precipitation (Pandžić et al., 2020; WMO, 2018).

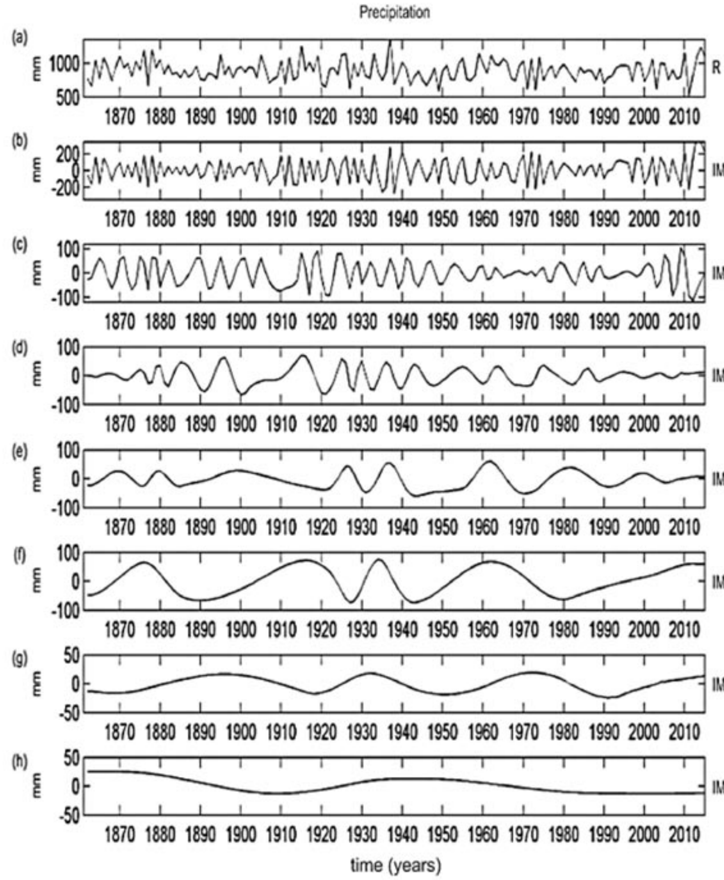

Figure 6. Data series of annual precipitation sums and its decomposition into IMFs, Zagreb-Grič observatory.

Slika 6. Vremenski niz godišnjih suma količine oborine i pripadni rastav na IMF-ove, opservatorij Zagreb-Grič.

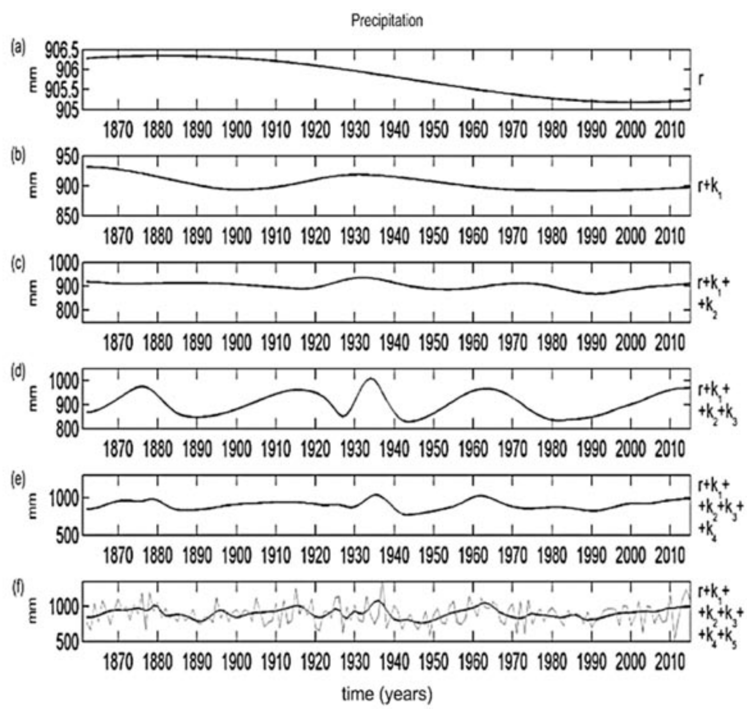

Figure 7. Same as in Figure 3, but for precipitation.

Slika 7. Isto kao slika 3 samo za oborinu.

4. VALIDATION OF HILBERT-HUANG TRANSFORMATION USING WAVELET ANALYSIS ON THE SERIES OF ANNUAL AVERAGES OF THE AIR PRESSURE

For a more complete display of the results, Hilbert transform is applied on IMFs obtained from annual averages of the air pressure. Using the EMD method on the series of annual averages of the air pressure at Zagreb-Grič observatory, no significant new results were obtained; nevertheless, the annual air pressure data are used in this section for the purpose of validation of HHT.

In order to validate such an approach, the Hilbert spectrum will be compared with wavelets in the last following two figures. To generate wavelet spectrum, a suitable program package from http://paos.colorado.edu/research/wavelets/ was deployed, while for HHT, free available MATLAB software from http://perso.enslyon.fr/patrick.flandrin/end.html was used.

Both Hilbert and the wavelet spectrum show amplitude, or energy distribution, that certain frequency has in time. These methods are applied to the annual averages of the air pressure, Figures 8 and 9. It can be seen that there is a relatively good match of the results obtained by both methods. Namely, the Hilbert and wavelet spectrum show similar frequency variations in time and display increase energy concentration around the year 1920, with an oscillation period of 3 and 7 years and, around the year 2000, with an oscillation period of 4 years; thus, loosely suggesting ENSO effects (e.g. Holton, 1992). However, there are some differences in the display and the results calculated by those two methods.

Wavelet analysis used wavelets, or short oscillatory waves, that overlap with signals at each point in time (Torrence and Compo, 1998). Most often, localized wavelets are sinusoidal, and the calculated frequency in that case is the frequency of the sinusoid that shows the best match with the signal. If analyzed, a wave profile at least deviates from that simple sinusoid; additional frequencies in the form of localized harmonic series are necessary in order to recover the related deviations. In this way, instantaneous frequency

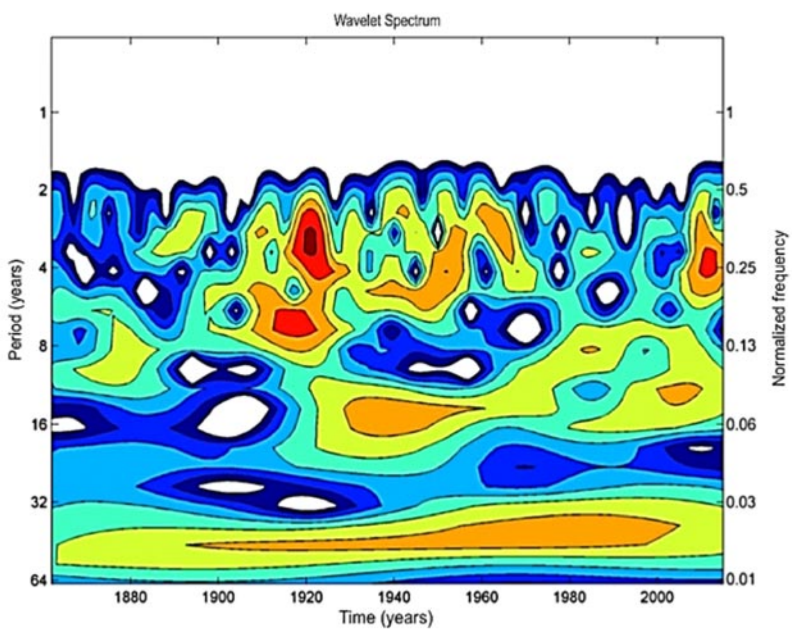

Figure 8. Wavelet spectrum applied to the IMFs obtained from annual averages of the air pressure, Zagreb-Grič observatory. The color intensity, representing the energy distribution, e.g. toward yellow and red, means larger energy.

Slika 8. Valićni spektar primijenjen na IMF-ove dobivene iz godišnjih srednjaka tlaka zraka s opservatorija Zagreb-Grič. Intenzitet boja predstavlja raspodjelu energije, pri čemu žuta i crvena označavaju veću koncentraciju energije.

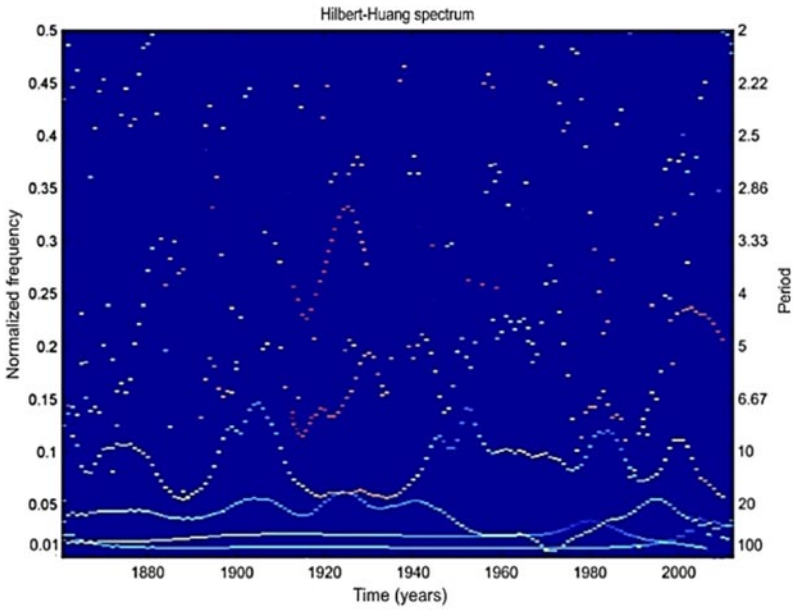

Figure 9. Hilbert spectrum obtained from the IMFs based on annual averages of the air pressure, Zagreb-Grič observatory (the period axis on the right is in years). Good agreement with Figure 8 can be seen. For example, both spectra show a concentration of energy around the year 1920, yet the wavelet, Figure 8, displays a spot, while Figure 9 gives finer structures and suggests more details than wavelet analysis (see the third curve from below that spreads the signal between 1920 and 1940).

Slika 9. Hilbert spektar dobiven od IMF-ova na temelju godišnjih srednjaka tlaka zraka s opservatorija Zagreb-Grič (na osi desno period je u godinama). Vidljivo je dobro slaganje sa slikom 8. Oba spektra pokazuju povećanu koncentraciju energije oko 1920. godine, međutim, valićni spektar na slici 8 prikazuje točku, a slika 9 finije i preciznije strukture (pogledaj treću krivulju odozdo u razdoblju 1920. – 1940.).

is actually an average frequency, while the width of the frequency belt reflects the degree to which the frequency deviates from that average. Wavelet spectrum in Figure 8 shows the frequency belt which contains primary energy of the wave, while lighter shades that fade towards higher frequency belt suggest energy distribution outside the dominant wave frequency. Because of such mooting, and because of the fact that wavelet transformation represents frequency's stationarity during a wavelet chosen, assessing instantaneous frequency with this method is often suboptimal.

Compared to the wavelet analysis, Hilbert spectrum HS has significantly improved frequency and temporal resolution. The main reason is the HS's ability to show instantaneous frequency, which enables one to display the frequency modulation within a single period. For the example of air pressure given, the instantaneous frequency modulation is most clearly visible in the light blue curve in Figure 9, the third from the bottom. Though it shows ≈ 20-year oscillations, changes of frequency inside that period are clearly visible. Also, such modulations are presented with thin lines, which enable more precise frequency identification and clearer temporal location of each change in frequency. As stated in Huang et al. (1998), a display of nonlinear distortions through instantaneous frequency modulation, provides a better and physically more meaningful interpretation of energy–frequency–temporal distribution.

5. CONCLUSION

Climatological data from Zagreb-Grič centennial observatory, in Zagreb, Croatia (e.g., WMO, 2018) are used in this study. The work continues on Gajić-Čapka (1993), Šinik (1985), Radić et al. (2004), Pandžić et al. (2020) and some other studies.

A relatively new method for spectral analysis is presented and deployed, Hilbert-Huang transformation, HHT. It is compared to a more standard method, i.e., wavelet approach. In addition to extending the time series and a significant part of methodology from Radić et al. (2004), we add the Hilbert spectrum (HS), wavelet analysis and compare the methods. These agree in all most important aspects of climate variability.

The main goal of this paper is to demonstrate validity of the methods deployed in order to promote further investigations and a consequent use of these methods. Our analysis largely confirms the existing findings about AGC over the area, which is a strong indication of the usefulness of this method.

Almost needless to say, NAO has important influence on the weather and climate in the Zagreb area; this issue has been studied by e.g., Ogrin and Sen (2015). During the positive NAO phase, the IMF expectedly shows higher air temperature, while during the negative phase the related air temperature is lower. In the case of cloudiness, IMF7 of the winter season shows clear correlation with NAO, while in the case od precipitation, a positive NAO index is related with reduced precipitation amounts in the Zagreb area. IMF7 captures the period of NAO index exchange, and correlates negatively with it.

For the period of at least the last 30–40 years in the analyzed signal, deviations from natural variability have been detected, that points to a most significant possibility of anthropogenic influences. Because of the changes in the composition of the atmosphere, the increase in air temperature occurs and, consequently, the increase in total cloudiness and reduction in precipitation amount is detected. By applying the second part of HHT, i.e., Hilbert transform, a consequently better physical (not numerical) resolution, that is allowed by the method of HHT, shows ever finer details in comparison to the standard wavelet analysis.

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