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SEASONAL PRECIPITATION FORECASTING BY SPECTRAL ANALYSIS OF THE LARGE WATER BODY LEVELS

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"If you want to find the secrets of the Universe, think in terms of energy, frequency and vibration."

– **Nikola Tesla**

1. INTRODUCTION

The present work considers applying a spectral analysis to seasonal precipitation forecasting by extrapolating the historical time series of its proxy data. The large lake water level data might be used instead of the precipitation totals over the watershed for which given lake presents the runoff drainage endpoint. Such approach may especially be helpful for the watersheds having a sparse rain gauge network and/or complex terrain, which restrict an accuracy of estimating the precipitation totals.

When a ratio between the precipitation runoff totals of certain geographic region and of one of its watersheds is assumed constant, a precipitation tendency forecast for such watershed may be extended for the whole region. For example, the Dead Sea watershed is representative for the whole SE Mediterranean region: the ratio between the precipitation runoff draining to the Mediterranean Sea and to the Dead Sea watershed may be assumed constant.

2. OUTLINE

The proposed method for the precipitation forecasting is described here by its application to the Dead Sea water level data for 1930-2019. After deseasonalizing and detrending the data, a spectral analysis is applied. The main spectral components reflect the main natural cyclic processes and their interactions. These processes, which affect the water level, firsthand affect precipitation. A spectral approach allows the numerous physical processes to be taking into consideration purely mathematically, with no need for a physical explanation. Yet, it is obvious that the main spectral peak may be assigned with the solar 22-y cycle, as will be shown below.

The other than precipitation factors, affecting the Dead Sea water level (all negatively) are the water consumption from its tributaries, infiltrating into the soil and evaporation from the Dead Sea surface and Dead Sea Works evaporation ponds. The first two factors are generally non-cyclic, thus not reflected on the water level spectrum. The third factor, evaporation, is generally seasonal and being removed from the water level time series by removal of the seasonal component which includes all seasonal processes.

The preprocessed input data is being decomposed into a set of the quasi-periodical partial time series of the main spectral components by applying the Butterworth filters accordingly to the pre-defined cutoff frequencies. Then, the fitting function for each main component is being found with the Nelder-Mead simplex algorithm. The partial fitting functions are added up and extrapolated. The extrapolated part of the resulting function is considered to display the precipitation tendency forecast for the coming season/s.

The proposed technique of seasonal precipitation forecasting was verified by its application to the Dead Sea water level time series truncated by August 1991, 2002 and 2018. In these tests, a precipitation forecast for one season worked well. The two-seasonal forecast may be considered as working sufficiently.

The main questions remain open: How to best decompose the data spectrum into the main spectral components? Which part of the spectrum may be considered a noise and/or ignored? For how many seasons this method may provide a reliable forecast, given the two previous questions answered?

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3. THE METHOD'S HISTORY

Back in the late 1980's the fishing industry of the former USSR had ordered from the Ocean-Atmosphere Interaction Lab., affiliated with the Leningrad Hydrometeorological Institute, LGMI (now the Russian State Hydrometeorological University) several long-term forecasting projects. These projects were aimed on predictions of the following elements: North Atlantic sea surface temperature (SST), Sea of Okhotsk ice coverage, Caspian Sea water levels, Volga River discharge etc. To accomplish these projects, a spectral analysis was applied to the historical time series of the elements to be predicted for a number of years to come. The very idea of applying a spectral analysis to the climatological time series analysis was not new to the world. The algorithm implemented at the LGMI consisted of the following steps, of out which the Steps 1 and 3 were carried out with FORTRAN while Steps 2, 4 and 5 - manually:

Step 1. Spectral representation of the input data which is the historical time series;

Step 2. Subjective identification of the main spectral components and their boundaries, or cutoff frequencies;

Step 3. Applying a Butterworth filter, designed for each spectral component, to obtain a set of the quasi-periodical partial time series whose sum would approximate the original input time series;

Step 4. Separate exploration of each partial time series:

(a) taking a graphical pattern of the last decade or dozen years as a template to graphically find its best historical analog;

(b) copying the pattern of few years following this historical analog;

(c) pasting this pattern as a forecast by adjusting it to the end of the partial time series;

Step 5. Adding up all the partial forecasts to obtain a final forecast.

This method was verified for each forecasted element – SST, ice coverage, water levels etc. - and showed its applicability for the long-term forecasting projects.

4. UPGRADING THE METHOD

The present work has rooted in the MSc research study (1995) which had been carried out in the Technion, Israel (Osetinsky, 1995). In that study, the possibility to predict the Dead Sea water level data was tested by applying a spectral analysis idea described above. The input Dead Sea water level monthly data for 1930-1994 were obtained from the Israel Hydrological Service. The gaps in the data were completed by the special scheme developed in that study.

The completed time series was treated accordingly to the classical decomposition scheme, i.e. as consisted of trend, seasonal, cyclic and residual components. The data was preprocessed for a spectral analysis by detrending and removal of seasonality, as detailed next.

After detrending with the piecewise linear function whose break-points were defined subjectively, only the 1959-1994 part of the data was used for the water level forecast experiment, because the linear trend appeared as changed significantly around the late 1950s – early 1960s. A seasonal component was removed by replacing the original value X_m of each given month "m" by its seasonally-averaged value calculated as $[X_{m-6}+X_{m+6}]/24+[X_{m-5}+X_{m-4}+\ldots X_m+\ldots+X_{m+5}]/12$ (Kendall, 1976).

A spectral analysis algorithm was applied to the preprocessed input. The Steps 1, 2 and 3 were carried out in the way described above. However, instead of the FORTFAN, the MATLAB package already available in mid-1990s, was used. Three main spectral components were defined and filtered: long-term, "quasi-11-year" and "quasi-5.5-year". The residual component was calculated by subtracting the sum of three main components, obtained as outputs of the corresponding digital filters, from the input data.

The MATLAB package allowed replacement of the manual forecasting technique described in Steps 4 and 5 in the previous section by the automatized fitting procedure. This procedure implements the Nelder-Mead simplex algorithm which allows fitting the data by a non-linear function. This procedure, however, requires from the user to provide both the function structure and initial simplex, or first-guess set of the function parameters. Given the quasi-periodical form of the partial time series of the main spectral components, each fitting function was obtained as a sum of two sinusoids. Thus, the resulting fitting function for the input data had presented a sum of eight sinusoids: two for each one of four spectral components.

The forecast for the Dead Sea water levels was found by extrapolation of the sum of the resulting fitting function and linear trend. It only left to verify how it would be relied on. In 1995, the verification was carried out by applying the method to the Dead Sea water level time series truncated by the summer of 1991, 1992, 1993. In part, it was shown that the Dead Sea water level's unexpected rise during the 1991/1992 rainy season might be predicted in the previous summer.

5. UPGRADING THE APPLICABILITY

The MSc research study described above was carried out in 1995 from the purely hydrological point of view. Its goal was to propose a method which would provide a seasonal forecast for the Dead Sea water level. The latter has, in its turn, the critical implications on location of the Dead Sea water interface with its coastal aquifer. Both issues, i.e. the water level and location of its interface, are crucial for the local resorts' infrastructure and road safety.

During the final stage of that research, its verification results, in part, the possibility of prediction of the water level rise of 1992, were shown to Prof. Ido Seginer (Technion), who had noticed that, first of all, the proposed method could help predict the extraordinarily high precipitation amounts of the 1991/1992 rainy season. This comment meant that the Dead Sea level data's cyclic components, taken alone as reflecting the precipitation-bearing processes, might be used to predict the regional precipitation totals' tendency. Following this conversation, the concluding chapter of that MSc research was rewritten by including the analysis of the extrapolated cyclic components only. In part, it was concluded, based on the 1995 forecast, on the dry year of 1998.

6. SOUTH-EASTERN MEDITERRANEAN PRECIPITATION FORECASTING

The present work demonstrates applying the aforementioned method of spectral analysis to the 90-year data of the Dead Sea water levels, 1930/1-2019/8. The 1930-1994 completed data were copied from the described above MSc thesis (Osetinsky, 1995), and the 1995-2019 data were downloaded from the Israeli Water Authority website (www.water.gov.il).

6.1 *Spectrum*

The power spectrum of the Dead Sea water level time series presents the contributions of the natural processes and artificial activities into its variability. The artificial activities, mostly the water consumption, have a non-regular character and therefore represented as a high-frequency noise in the fading part of the level spectrum which therefore ignored as non-related to the precipitation-bearing processes.

Figure 2 shows the spectral representation of the original time series and the effects of deseasonalizing and detrending.

Deseasonalizing. Comparison between two first pairs of subplots in Fig. 2 shows that removal of a seasonal component not only eliminates the one-year peak, but also smooths the whole spectrum. This effect is a product of a sampling process, which distorts the ideal picture of the analogous case. In theory, a seasonal component is very strong and independent of any other cycle and must be, theoretically, presented by a narrow peak, close to the delta function, with steep lobes and no interactions with other cycles. The third pair of subplot allows zooming-in in the detrended time series and shows that removal of a seasoned component yields weakening the power of all cycles shorter than 2 years.

Detrending. The almost 90-year water level monthly time series was detrended by the 3-degree polynomial trend, instead of the described above (Osetinsky, 1995) piecewise linear trend requiring the subjective locating the break-points. The polynomial approximating function is practically the same for the deseasonalized and non-deseasonalized time series of as long as 90 years.

Comparison of third pair of subplots with the first two pairs in Fig. 2 shows that, after detrending, all spectral components have been weakened by more than one order of magnitude. It explained by the non-linearity of the function chosen for approximating the downward trend. The bottom subplot in Figure 2 shows dividing the spectrum into the main components.

Note: It is worth to mention that we first tried to apply a spectral analysis directly to the Jerusalem precipitation record which is one of the longest and representative for the SE Mediterranean precipitation. This long record was produced by combining the records from the numerous rain gauges each of them had been operated in the city during some period. Jerusalem is the most representative regional spot because of its location on the axis of the Judaean Mountains range between the Mediterranean and Dead-Sea slopes. We have found that the high-frequency part of the Jerusalem precipitation spectrum is more powerful than its low-frequency part. This means that the supposed results of the direct frequency analysis of the precipitation time series would be undermined.

6.2 *The main spectral components*

Several options were tried for dividing the spectrum of the Dead Sea water level data into the main spectral components. This subjective step is critical for all further automatized analysis. Here, we will describe only the main spectral components defined as optimal at the time of preparing this work. It is fairly possible that there is a better solution.

The first main spectral component is lowpass and has a peak corresponding to a 22-year cycle. It is quite obvious that this peak may be associated with the 22-year solar cycle. This cycle was not so clearly reflected in the MSc research study described above, with the data of 1959-1994, because the time series must be at least three times the length of the longest cycle recognized on the spectral representation of the process.

The second main spectral component is bandpass and has a peak corresponding to about 12.7-year cycle.

The third main component is bandpass and has a peak corresponding to about 8.1-year cycle.

A spectral segment to the right to the cutoff frequency corresponding to the 7.4-year cycle is considered a noise and ignored.

The numerous experiments with various divisions of this spectrum and other than 3 number of the main spectral components, have produced the results worse than those shown in in Figs. 3 and 4.

Each main spectral component is being separated with the Butterworth filter designed accordingly to the pre-defined cutoff frequencies shown in Fig. 2. The best results were obtained with the filter order of 2.

6.3 *Search for a fitting function*

Like in the 1995 research described earlier in the text, the fitting function for each main spectral component was found with the Nelder-Mead simplex algorithm. For each component, the applied function structure was defined as a sum of two sinusoids. The first-guess set of six parameters - amplitude, frequency and phase for each sinusoid - was derived based of the form of the filtered time series obtained after applying the corresponding filter.

The resulting fitting function, obtained by adding up all partial fitting functions, was then extrapolated for several years.

7. RESULTS

The whole algorithm was verified for the rainy seasons of 1991/1992, 2002/2003, and 2018/2019 by truncating the input half a year prior to the verified rainy season. That is, for these three verifying experiments, the Dead Sea level monthly time series was truncated by Aug 1991, Aug 2002, and Aug 2018, respectively. The forecasted tendency of the extrapolated fitting function was found to be well correlated with the regional precipitation totals' tendency. (Though a direct spectral analysis of the precipitation time series, either for individual stations as noted before or regional totals, derived from the available records, was found as being much less promising).

8. CONCLUSIONS

The SE Mediterranean precipitation is typically of a convective type. This makes using the regional rain gauge records hardly effective for producing a regional seasonal forecast. Applying the proposed technique for even such a representing rainfall record as of Jerusalem, produces much more white-noisy spectrum than that of the Dead Sea levels. The various spatial techniques for constructing a regional representing precipitation time series yielded the dissimilar results, while the Dead Sea level data (preprocessed as shown), accounting for streamflow and runoff over the complex terrain of the region, might serve as a workable proxy for a regional precipitation forecast.

We have investigated a possibility of applying of this method to two-year forecasting. The possible approach for increasing a reliable forecasting period may be optimization both of a spectrum division and of the first-guess set of parameters for the Nelder-Mead simplex method.

For the one-seasonal forecast, the described method is definitely may be recommended.

9. DISCUSSION

Open questions still remain:

Is it worth using the whole available data or only the last decades?

Which frequencies might be considered noise and disregarded?

How to best estimate a first guess set for the Nelder-Mead algorithm?

How to quantify the precipitation totals' forecast out of the water level tendency forecast, besides the qualitative estimation?

10. REFERENCES

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Karpova, I.P., Y.V. Sustavov, D.L.Nicolaev, 1991: Using the Time Series Extrapolation Techniques in the Long-Term Prediction Methods. In*: Methods of Computations and Predictions of Hydrometeorological Processes in Fishing Regions*. LGMI, Leningrad.

Kendall, M, 1976: Time Series, *Charles Griffin*.

Figure 1. The Dead Sea historical watershed location. Credits: https://thenaturalhistorian.com/2014/09/03/dead-sea-origins-strangest-geological-features-earth/.
The Dead Sea is a hypersaline lake presenting the lowest spot of its closed watershed and located in Israel and Jordan. The northern part of the Dead Sea historical watershed extending up to the Mt. Hermon and located in Israel, Lebanon and Syria presents now the separate watershed of the Lake of Kinneret (Sea of Galilee). These two watersheds are being separated by the Degania dam constructed at the Kinneret southern coast in the 1930s. Since then, the dam has been opened only few times and for a short while to allow the Kinneret excess water to be flown to the Dead Sea. These rare events have no influence on the Dead Sea water level spectral representation because only the strongly cyclic processes are explicitly reflected in the spectral peaks. (The minor water amounts pumped regularly from the Kinneret watershed into the bypass to maintain certain sites of the lower Jordan River do not reach the Dead Sea at all.)
The very southern tip of the Dead Sea watershed is located in Egypt (Sinai Peninsula).

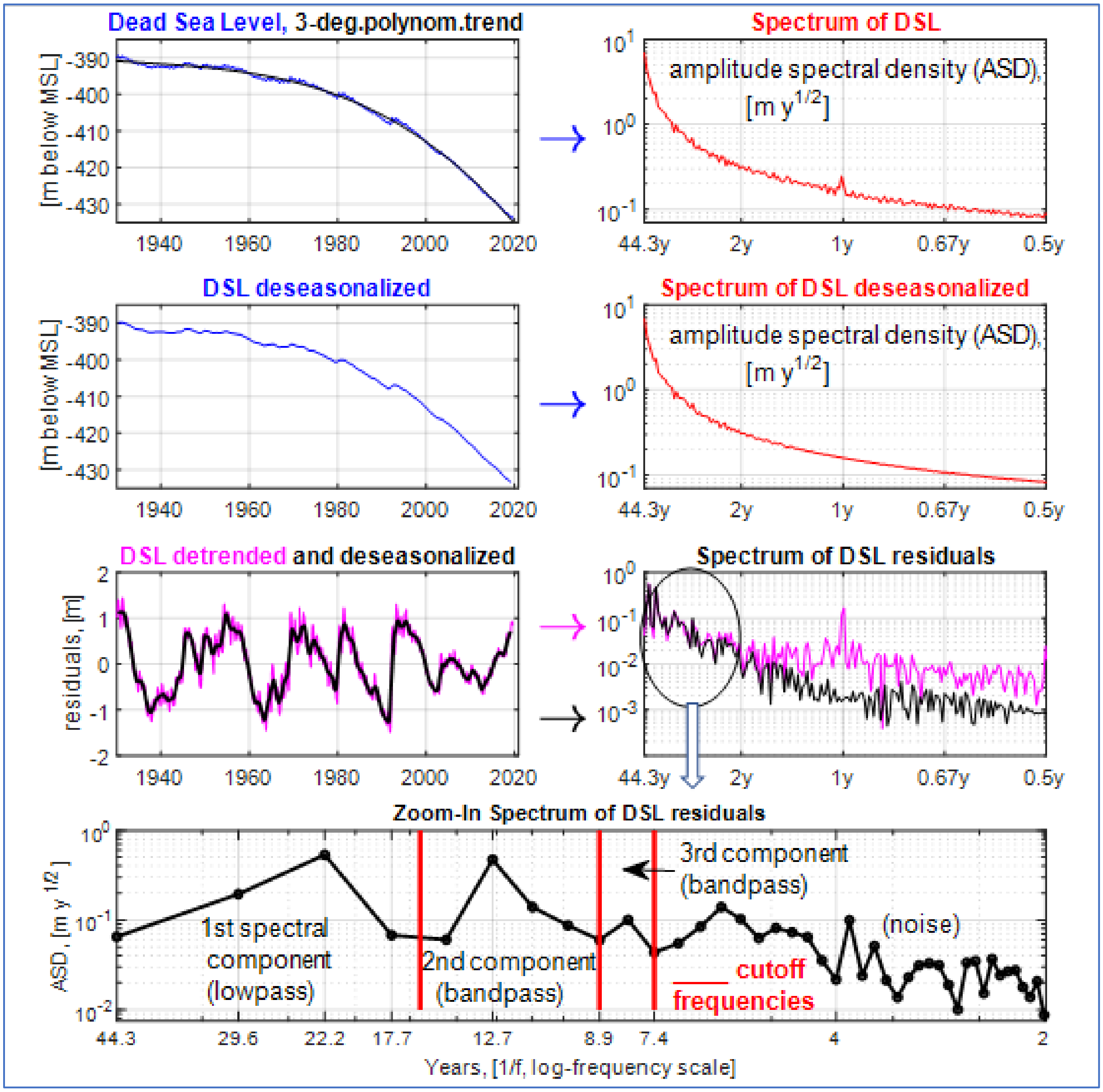

Figure 2. Paired subplots: comparison of spectral representations of the original, deseasonalized and detrended data. For convenience, the frequency axis is labeled in the terms of years.
Bottom subplot: spectrum division defined as optimal at the time of preparing this work. For convenience of manual pre-defining the cutoff frequencies, the frequency axis is log-scaled. This subplot shows the low-frequency segment of the spectrum, limited by a frequency corresponding to the 2-y cycle.

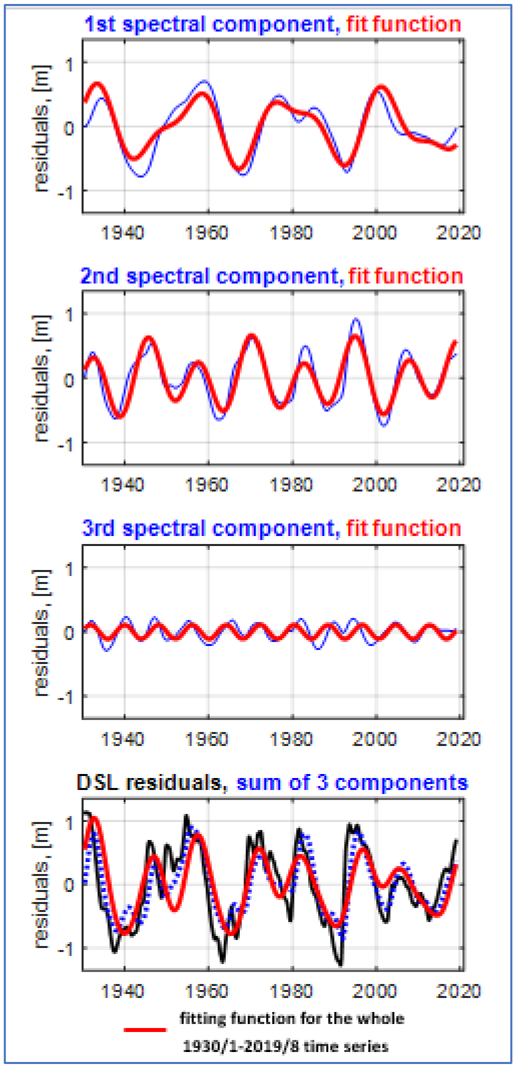

Figure 3. Fitting function for each one of three main spectral component and their sum.
Legend as in colored titles

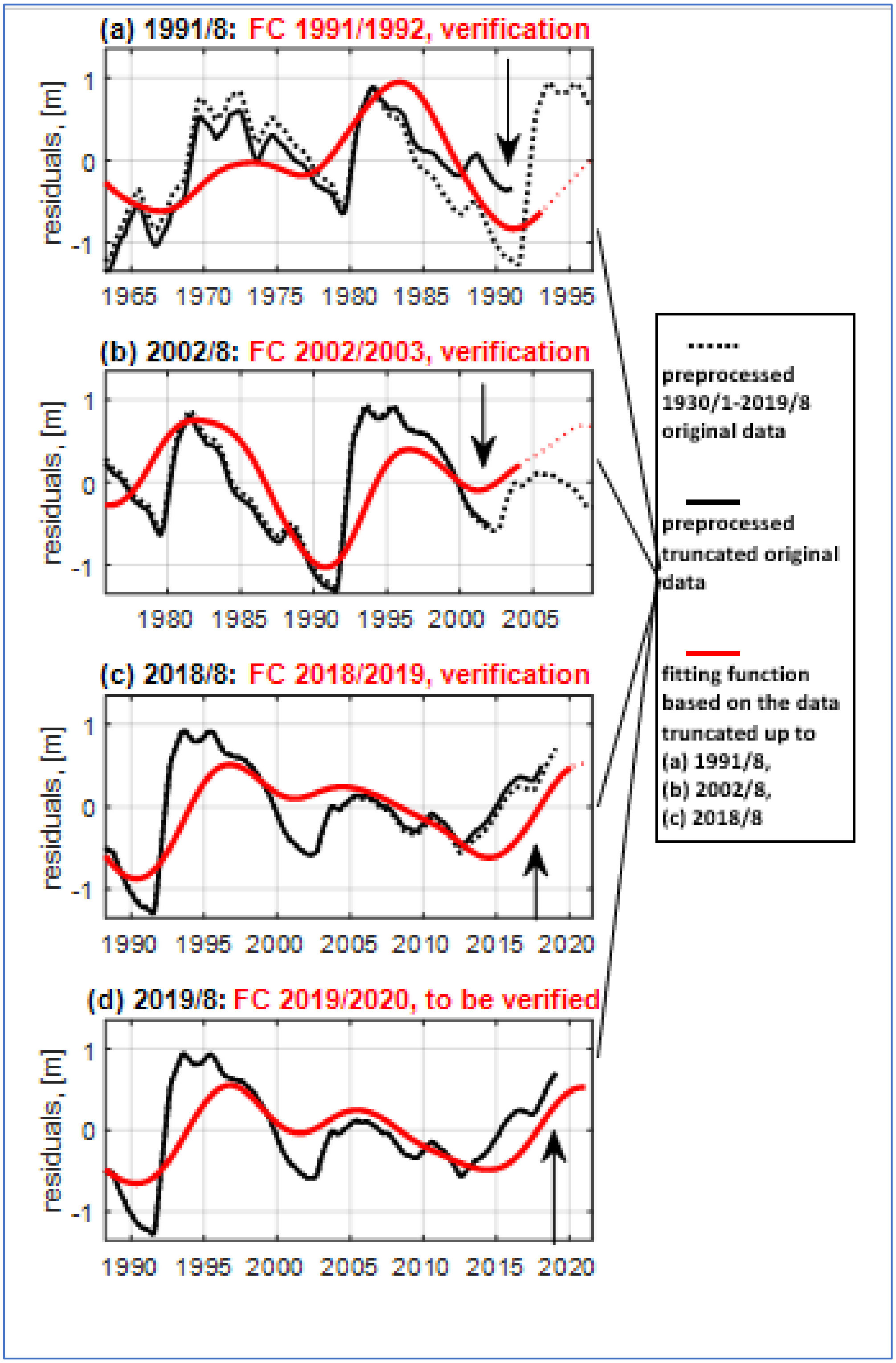

Figure 4. Verification for the rainy seasons of 1991/1992, 2002/2003, 2018/2019, and forecast for 2019/2020.