Using the Fast Fourier Transform Technique for Climate Time Series Decomposition

E.K. Elmaghraby a, S.A. Abu Khadra b, and H.S. Eissa b

a Experimental Nuclear Physics Department, Nuclear Research Center, Atomic Energy Authority, Egypt
b Radiation Protection Department, Nuclear Research Center, Atomic Energy Authority, Egypt

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ABSTRACT

A twenty years investigation of the evolution of regional climate is performed by applying fast Fourier transform signal decomposition technique to the discrete meteorological data. The technique was applied to the pressure, temperature, humidity, wind direction, and solar irradiance signals, acquired by meteorological station located in Inshas location, Egypt (30.289° N, 31.291° E). The low-frequency components of each signal show slight changes in its respective signal. Even with these slight changes in the local temperature, humidity, and pressure, a major change in wind direction is recorded. These findings could alter the performance of any proposed wind power stations. The results showed that the climate became warmer about 1.2 °C than it was twenty years ago.

Keywords: Climate Disequilibrium, Annual Variation, Fast Fourier Transform, Signal Processing.

INTRODUCTION

The earth's climate was thought, long time ago to be a grand stable equilibrated system with cycle durations ranged from one day to hundreds of years. Human activities during that time were too little to affect the equilibration of that system. In the last century, mankind made and continues doing evident effects on the earth's system which cannot be compensated. Although, the earth's climate variables are strongly correlated, the variation may take long time to be observed and cause serious consequences. It affects the human life, wind energy resources(1,2), water resources(3-5) as well as environment (6). The term `climate change¨ is occasionally used instead of `global warming¨ pursuant to the alterations of local or global climate. To handle the climate changes today, it is vitally important that climatologists gain good understanding of the mechanisms that caused past climate change, putting the earth repeatedly into or out of disaster. Through understanding these natural cycles, scientists are able to comprehend them. This knowledge, in turn, allows them to understand the science of global climate change(7), a necessary step to solving the problem. In the present work, the method of Fast Fourier Transform (FFT), as a multiresolution signal decomposition, was used in order to study the short-term evolution of the climate variables.

MEASUREMENTS

Data values are recorded using a continuously running station located at Inshas site, Egypt (30.289° N, 31.291° E) about 5 m above two level building (12 m above the ground) and surrounded by very low density building area (The maximum height of buildings within area of 10 km in diameter is less than four flours). Data presented and analyzed in the present work were acquired during the period from first of January 1990 to March 2010 using the mentioned climate station with a measurement uncertainty of about 0.1-0.2 kPa for pressure, 5-7% for humidity, 2-4 degree for temperature and 2-4° for wind direction, for each record. The temporal resolution of the primary data was 15 minutes.
PROCEDURE

Due to the presence of periods of repair and maintenance, data were not recorded constantly. On the other hand, for applying Fourier transform filtering, data needs to be discrete with equal duration (even data set.) To overcome this problem, we used an averaging procedure that gives the mean value of the observable from preceding and subsequent years at the same date and time. Additionally, random value between $-\varepsilon$ and $\varepsilon$ was added to the missing data, where $\varepsilon$ is the maximum uncertainty of each observable. Adding such random errors prevent the inverse resonances that may appear by using the fast Fourier transform algorithm.

The basic concept here is to divide the signal spectrum into its subspectra (or subbands), and then to treat those subspectra individually for the purpose at hand\(^{(8)}\). From a signal coding standpoint, it can be appreciated that subspectra with more energy content deserve higher priority (or weight) for further processing. For example, a slowly varying signal will have predominantly low-frequency components. Therefore, the low-pass subbands contain most of its total energy.

The analysis is obtained by applying the low-pass fast Fourier transform filtering (L-FFT) to each level (see Ref. \(^{(9)}\). Filtering is a process of removing some frequency components from the signal. The L-FFT filtering procedure includes transforming the signal from the time domain to the frequency domain using fast Fourier transform, applying the low-pass filter, and restoring the resultant frequency spectrum into the time domain using the inverse fast Fourier transform. Selecting the cutoff frequency of the low pass filter is guided by our sensation of temporal variation of climate variables. Cutoff frequencies of the order 365 y\(^{-1}\), 12 y\(^{-1}\), 4 y\(^{-1}\), and 1 y\(^{-1}\) are used. The ORIGIN program was used to filter the data using FFT algorithm. Figure 1 shows fast Fourier transform as a multiresolution dyadic tree with L and H represent low- and high-pass filters, respectively.

![Block diagram showing the procedure of the FFT decomposition. H and L refer to high- and low-pass filters, respectively, s[n] is the input signal, A_x[n] is the approximation vector, D_x[n] is the details vector, and x is the level of decomposition](image)

Fig. (1): Block diagram showing the procedure of the FFT decomposition. H and L refer to high- and low-pass filters, respectively, s[n] is the input signal, A_x[n] is the approximation vector, D_x[n] is the details vector, and x is the level of decomposition

Hence, from our perspective, we view successive Fourier filtering as a decomposition technique and the discrete-time signals as suggested in Fig. 1. The low-frequency signals obtained with the L-FFT are more smoothed and do not have significant edge effects. Description of the results will follow the cause and effect sequence, i.e. temperature, humidity, pressure, wind direction, and solar radiation.

RESULTS AND DISCUSSION

Fortunately, the basic cycle durations of the meteorological observables are "approximately" known. It is either, daily, weekly seasonally, and yearly. So that, we prepared an L-FFT with cutoff frequencies 365 y\(^{-1}\), 12 y\(^{-1}\), 4 y\(^{-1}\), and 1 y\(^{-1}\).

1. Temperature Variation

Decomposing the temperature signal revealed unknown alteration in winter of 2003, 2004 and 2005 appeared in the A_1 component of the signal. These winter alterations are mirrored in the summer of subsequent years (2005, 2006 and 2007). A very small increase in temperature is observed in the A_3 level of the decomposition. The straight line in the A_3 plot in Fig. 2 shows 1.2 °C increase in the average temperature during the investigated period. This increase in the average temperature is unfeasible to be obtained from the original temperature signal.
Fig. (2): Decomposition of temperature signal into its daily, monthly, seasonally, and yearly approximations and details

Such shift in the average temperature lay within the experimental error (5-10%) of a single measurement and may not be considered important. However, due to the nature of the FFTF, of being an averaging procedure, the uncertainty is reduced by a factor of $1/\sqrt{N}$, where $N$ is the number of measurements (in the present case $N \approx 20000$, i.e. the uncertainty in the local temperature increase is within the uncertainty 0.01-0.03 °C (taking into account average temperature of 30 °C).

Even though the temperature is changed few degrees, it may not seem for the public a big problem. However, if one knows that in the last ice age, for instance, the average temperature was only about 4 - 6 °C cooler than that is to day, the change of one degree Celsius become a terrifying effect. The main action of the temperature change lies in the position in which the temperature crosses 0 °C during its seasonal variation, the region of phase transition of water. Nowadays, these regions are adjacent to the earth’s polar circles. Whenever the average temperature changes cause phase transition of water, the solid ice mountains begin to strew about the oceans, in an irreversible behavior. Another consequence of the global warming is the increase of evaporation and evapo-transpiration, causing loss in humidity of soil and irrigated area as well as open aquatic areas.

2. Humidity Variation

During the period 1990-1997, the measurements of humidity was performed manually at 7:00 am, while for the rest of the investigated period the automated system measure the relative humidity every 1 hour. The variation of relative humidity (RH) is not as random as we thought. According to the $A_1$ and $A_2$ levels of decomposition, there is a periodicity in the humidity signal as mentioned in the $A_1$ component of the RH signal, as clear from Fig. 3. The alteration began in summer 2004 and continued to be varying during the following years. Seasons of the increase in RH are changed. On the other hand, the average RH variation, given by the $A_3$ component in Fig. 3, had a general decreasing trend. The value of RH decreased through the investigated period from 60% to 55%. Such variation in relative humidity has an experimental error 0.05-0.07% due to the nature of the FFTF of being an averaging procedure.
3. Barometric Pressure Variation

The variation of the barometric pressure, which may be connected to relative humidity, follows the same sort of cycling pattern. In Fig. 4, the $A_1$ component of the pressure signal is important. The variation that began in the winter of 2004 persists since that time. The general trend of the pressure is observed in the $A_3$ component of the decomposition. The variation of barometric pressure, apparently, counters the variation of humidity. That relation is because moist air is less dense than dry air. Consequently, the less dense air creates delayed upward buoyancy force that results in the increase of pressure as reaction force.

Fig. (3): Decomposition of relative humidity signal into its daily, monthly, seasonally, and yearly approximations and details

Fig. (4): Decomposition of barometric pressure signal into its daily, monthly, seasonally, and yearly approximations and details
The variation of the average barometric pressure may be confusing. During the years 1991-2010, a constant value of the A\textsubscript{3} component is observed while beginning from the 2003 winter, a continuous linear increase in the barometric pressure is observed and continues until 2006 summer. The average increase during this period was three mb. The pressure raised at a with larger rate during the period 2006-2010. The uncertainty within these value of pressure is between 0.5 and 1 mb. The increase in barometric pressure may be urged to the persistent decrease in the relative humidity around the area under investigation.

4. Wind Speed and Direction Variation

There is about three mb increase in the barometric pressure, i.e. less than 3%. However, this small variation causes a disaster in the wind direction. Figure 5 shows the decomposition of the wind signal. The 2006 effects that were observed in barometric pressure caused delayed consequences in the wind direction. The delayed wind direction effect began at the end of the year 2006 as seen in the A\textsubscript{3} component of Fig. 5. The general wind direction has been changed from 170° (i.e. coming from north-west, going to south-east) to be 220° (i.e. coming from north-east, going to south-west). Such great change can modify decisions made by governments and the public concerning the location of wind power stations that exploit the wind to generate electric power, and location of nuclear power station to avoid any probable spread of radioactive materials to populous cities. Even decisions concerning the construction and position of buildings may be affected. Another related reason is the construction of new puddings in the area which lowers the wind speed as shown in Fig. 6. The decrease in wind speed began in 2001 and continued to the end of the investigated period.

![Decomposition of wind direction signal into its daily, monthly, seasonally, and yearly approximations and details](image)

Fig. (5): Decomposition of wind direction signal into its daily, monthly, seasonally, and yearly approximations and details
5. Solar Radiation

Humidity (moisture or clouds) strongly modulates the earth’s radiation budget through their interaction with solar radiation. The presence and variations of cloud coverage and cloud radiative effects are closely related to atmospheric humidity as mentioned by Sun et al., 2000(13) and Groisman et al., 2000(14). In general, any variation of solar radiation, that received by the earth's surface or absorbed by the lower atmospheric layer, will affect the climate and causes large changes. An additional factor which is the sun magnetic field during the time of solar activity is important and leads to altering the climate state. That factor has mainly geomagnetic and ionosphere consequences(11), which takes longer time to alter the troposphere.

Fig. (6): Decomposition of wind speed signal into its daily, monthly, seasonally, and yearly approximations and details

Fig. (7): Decomposition of solar radiation signal into its daily, monthly, seasonally, and yearly approximations and details
Figure 7 represents the upper envelope of the solar power irradiance during the period 1991-2010. It is apparent from Fig. 7 that the solar radiation power on the earth's surface was increased during the period 1991-2003. A sudden decrease is obvious during the years 2004-2005 follows by an abrupt increase during 2006. The change in solar radiation power is a result and a cause at the same time due to the mutual dependence among climate variables. Retrieving the solar activity data (cf. Willson, 2011 Ref. (13)), one can conclude that the 2003 disturbances keep company with the peak of solar activity. The total extraterrestrial irradiance has the same fluctuation that altered the regional climate state in our measurement location.

There is no single scenario that could describe the trend of dependencies among climate variables. There would be a thermodynamic equilibrium between solar radiation from one side and all other climatic variables from the other side. Any disturbance needs a long time to be recovered, if it is recoverable. For instance, the increase in temperature causes an increase in the ability of air to carry water vapor (i.e. decreases the relative humidity for the same amount of water vapor.) However, the 2% decrease in the relative humidity cannot be related to the 1.2 °C increase in the temperature during the investigated period. The change in wind direction from 170° to 220° during the investigated period can participate to such change. Globally, with considering the earth's system as a huge thermodynamic system, the amount of heat gained by solar radiation is not equal to the amount of dissipated energy in the space. As a result, there are increases in the entropy of the earth's system as a whole and as parts. It seems that any change in the climate has an irreversible nature which is associated with an increase in entropy of the system. Hence, it is not only the continuous increase in carbon dioxide that may cause the climate change; any undulation in the rate of variation may cause unpredictable consequences.

**CONCLUSION**

Local climate contains components that are often distinguished from one another on temporal scales rather than spatial. The multi-resolution signal decomposition technique is used to extract the short-term inter-annual atmospheric signals. Results showed that an early evolution of the regional climate change appeared in winter 2004 as revealed from the A_3 components of the temperature, humidity, and pressure signals. This variation causes a change in the wind direction from 170° (i.e. coming from north-west, going to south-east) to be 220° (i.e. coming from north-east, going to south-west). The change in wind direction should be taken into account in the forthcoming wind power stations that are proposed to be installed in Egypt.

These results give preference to the technique of multi-resolution signal decomposition to have a great applicability on analyzing meteorological data through decomposing it into its daily, monthly, seasonally and yearly varying components.

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