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Evaluation of the Annual Correlations between Different Solar-Ionospheric Indices During Solar Cycles 23 and 24

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Abstract

In this work, the annual behavior and cross-correlation between three different solar-ionospheric indices were evaluated: Smoothed Sunspot Number (SSN), Ionospheric T-Index (T-index), and Solar Flux (F10.7 cm) index during solar cycles 23 and 24. The annual behavior for the three tested indices of the maximum and minimum years of the two solar cycles was studied. The correlative conducts between the studied indices were evaluated for the studied periods (1996-2008) and (2008-2019) of the 23rd and 24th solar cycles. The annual correlation between the studied indices was represented by the linear regression equation. The suggested mutual correlation equation gave a good agreement with the observed annual average values of the tested indices. The statistical calculation results of the calculated datasets of the tested indices showed very good results for all statistical parameters. The evaluation of the annual correlations between tested solar-ionospheric indices showed that the tested indices are mutually and linearly correlated to each other and can be predicted reciprocally depending on the suggested mathematical correlated equations.

Keywords: Smoothed Sunspot Number, Solar Flux 10.7cm, T-index, Solar cycle, Solar activity.

تقييم العلاقات الارتباطية السنوية بين مختلف مؤشرات الغلاف الأيوني - الشمسية خلال الدورات الشمسية 23 و 24

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الخلاصة

في هذا العمل، تم تقييم السلوك السنوي وألارتباط المتبادل بين ثلاث مؤشرات مختلفة للغلاف الأيوني-الشمسي: وهي عدد البقع الشمسية (SSN)، ومؤشر T (T-index) والتدفق الشمسي (F10.7) خلال الدورات الشمسية 23 و 24. تمت دراسة السلوك السنوي للمؤشرات الثلاث المختبرة للسنوات القصوى والدنيا للدورتين الشمسيتين. حيث تم تقييم العلاقات الارتباطية بين المؤشرات المدروسة للفترات (1996-2008) و(2008-2019) للدورات 23 و 24. لقد تم تمثيل العلاقات الارتباطية السنوية المتبادلة بين المؤشرات المدروسة بمعادلة الانحدار الخطي. أعطت معادلة الارتباط المقترحة توافقاً جيداً مع متوسط القيم السنوية المرصودة للمؤشرات المختبرة. بينت نتائج الحساب الاحصائي لمجموعة البيانات المحسوبة للمؤشرات المختبرة نتائج جيدة جداً ولجميع

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المعلمات الاحصائية. لقد أظهر تقييم الارتباط السنوي بين مؤشرات الغلاف الايوني–الشمسي المختبرة ان المؤشرات المختبرة مرتبطة ببعضها البعض بشكل متبادل وخطي ويمكن التنبؤ بها بشكل تبادلي اعتماداً على المعادلات الرياضية الارتباطية المقترحة.

1. Introduction

Solar activity indicates to any natural event occurring on the sun such as sunspots, solar flare, solar flux 10.7 cm, energetic particles, and coronal mass ejection [1]. It is mostly paid through the variability of the sun's magnetic field. Sunspots are locations on the sun's photosphere that look darker than the surrounding areas on the visible solar disk due to lower surface temperatures linked with magnetic field flux concentrations and magnetic activity that is extremely high. The number of sunspots has a cyclical increase and decrease over an approximately 11-year period known as the solar cycle [2]. The sunspot cycle (Cycle 24) has been considerably weak [3].

Solar activity and geomagnetic activity are disturbances caused by variations in the magnetic fields of the sun and the planet respectively. Both activities are linked through the interplanetary medium that lies between the sun and the interstellar medium. Strong solar transient eruptions are used to measure the sun's activity. Coronal mass ejections, solar wind streams, and solar flares are all associated with massive amounts of energy and mass. The frequency and intensity of transient solar emissions fluctuate with the solar cycle's phases, which are defined by the number of sunspots on the surface of the sun [4]. Solar and ionospheric indices are used to furnish a more or less detailed description of the parameters needed for a radio connect [5].

The sunspot number (R), is also named the Wolf number allusion to the Swiss astronomer Johann Rudolf Wolf or Zurich sunspot number (R_Z), is obtained from the observatory's position. Since both can be observed from the ground and lengthy data records exist, the radio flux at (10.7 cm) wavelength, (F10.7 cm) is the most widely utilized one.

Ionospheric indices are widely used and recommended for ionospheric long-term studies and predictions. The ionosphere is highly variable and deviations from monthly medians can reach 20-40 % during quiet times and even larger values during disturbed times (geomagnetic storms). There are a variety of ionospheric indices of which the best known are IF2 and the T-index. Ionospheric indices are effective because the F layer is strongly dependent on changes in solar activity. Radio and Space Services of the Australian Ionospheric Prediction Service (IPS) developed the T-index to generate predictions of the ionospheric characteristics f_oF_2 and M(3000) F_2 for any time and location in the world [6]. Bruevich, E., et al. (2018) studied the long-term variations of several solar activity indices that have been measured over the last 40 years. The results of various solar studies showed the presence of short and long-term trends in the time dependence of activity indices during the studied period [7].

Geomagnetic indices are basic assessments of magnetic activity that occur over short periods, often less than a few hours, and are measured using magnetometers at ground-based observatories. Geomagnetic indices are routinely used across the many sub-disciplines in geomagnetism, including direct studies of the physics of the upper atmosphere and space. There are a variety of geomagnetic indices, some of which are: (D_{st}) represents the level of a geomagnetic storm, (AE) characterizes the Auroral Electrojet activity, and (PC) describes the Geomagnetic activity over Polar Caps [8]. Mardan, M. K., et al. (2018) studied the impact of the solar activity on the temperatures of the ionospheric electron, ion, and neutral particle over Iraqi region using different ionospheric models. The computed parameter values were based on the observed Smoothed Sunspot Numbers (SSN) and the solar flux (F10.7) indices. The study's findings revealed that the solar activity of the chosen years had a minor influence on the ionospheric temperature parameters [9]. Sharma, S. K., et al. (2020) studied the variation and correlation between ionospheric Total Electron Content (TEC) and different solar indices over the Saudi Arab region. The correlation results between the total electron content and solar indices showed that the solar Extreme Ultraviolet (EUV) flux is the better solar index parameter [10]. Mohammed, F. A. (2016) studied the relationship between electron density and solar indices international sunspot number (Ri), Northern hemisphere sunspot number (Rn) and Southern hemisphere sunspot number (Rs) for D-region over baghdad city during the descending and ascending phases of the 23rd solar cycle. The results showed that a very strong direct relationship between (Ri, Rn, Rs) with an electron density of D-region (NmD), that is, the three solar indices can be relied upon to predict (NmD) [11]. Okoh, D., et al. (2020) studied the relationship between sunspot number (SSN) and solar flux at 10.7 cm (F10.7) by using regression analysis and neural network training procedures. The findings indicated that F10.7 values can be predicted from (SSNs) using neural networks [12].

2. Smoothed Sunspot Number (SSN)

The development of the solar cycle can be registered by the sunspot number. The sunspot number is a worldwide indicator of solar activity obtained from optical measurements of the visible disk of the sun [13]. The sunspot number is defined daily by the equation introduced by Wolf (1861):

$$R = k\,(10\,N_G + N_s) \qquad \text{…….. (1)}$$

Where (R) is sunspot number, (N_G) is the number of sunspot groups, (Ns) is the number of individual sunspots, and (k) is a correction factor that varies depending on location, observer procedures, and instrumentation [14]. Daily sunspot number is recorded monthly, and yearly averages are determined. Each Smoothed Sunspot Number is an average of (13) months [15].

3. Ionospheric Index (T-index)

The T-index is an indicator of the highest frequencies able to be refracted from regions in the ionosphere. The index is calculated using ionogram measurements of ionospheric f_oF2. It's also utilized in the IPS forecasts, and it's updated monthly [16]. Additionally, the T-index may be thought of as an “equivalent sunspot number” or the sunspot number that best matches the measurements provided by ionosondes. IPS has a network of ionosondes located in the Australasian district and can derive the most suitable T-index. Low T-index values mean the use of lower HF frequencies such as around solar minimum or during a severe ionospheric storm. Higher T-indices and therefore higher frequencies will usually be near solar maximum [17]. Thabit, S. A., et al. (2021) have identified the Optimal Reliable Frequencies (ORF) of the year for various transmit/receive stations located in various regions in Iraq. The calculated parameter values are based on observations of the ionosphere (T-index) and the results of this simulation show that the proposed ORF parameters are represented by polynomial equations of different orders [18].

4. Solar Radio Flux (F10.7 cm)

The 10.7 cm solar flux is vastly utilized in upper atmosphere studies as a measure of the solar Extreme Ultraviolet radiation (EUV), whose variations are accountable for significant changes in properties above 200 km. F10.7 is a general indicator of solar magnetic activity, solar ultraviolet and X-ray emissions, and even solar irradiance. Hussein, Z. F. (2019) studied the relation between Coronal Mass Ejections (CMEs) and Smoothed Sunspot Number (SSN) during the 24 solar cycle. The results indicated that the annual correlation between (SSN) and (CMEs) is simple and can be expressed by a linear regression equation [19]. F10.7 is used for a wide range of applications including astronomy, climate modeling, geophysics, meteorology, communications, satellite systems, and so on. The sun's electromagnetic radiation at a frequency of 2800 MHz and a wavelength of 10.7cm is an important parameter for determining the level of solar activity. The strength of solar F10.7 is expressed by solar radiation flux at a wavelength of 10.7 cm. The 10.7cm observations began in 1947 [20]. Therefore, F10.7 is a good indicator to measure general solar activity [21].

5. Test and Results

This paper evaluates the nature of the annual correlation between three different solar-ionospheric indices. This work aims to study the nature of the annual behavior of the tested indices and evaluate the correlative conduct between them. The research also aims to reach mutual correlative relationships between the tested indices. The annual behavior for the three selected indices was studied for the maximum and minimum years of solar cycles 23 and 24. The dataset of the tested indices (Smoothed Sunspot Number (SSN), Ionospheric T-Index (T-index), and Solar Flux (F10.7)) were obtained from the following websites: The SSN dataset values were got from the World Data Center-SILSO (WDC-SILSO), Solar Influences Data analysis Center (SIDC), Sunspot Index and Long-term Solar Observations (SILSO) https://www.bis.sidc.be/silso/datafiles, while the T-index and the F10.7 values were taken from the Space Weather Services (SWS) (formally known as IPS Radio and Space Services, Ionospheric Prediction Services (IPS)) https://www.sws.bom.gov.au/Solar/1/6 and the Space Weather Prediction Center (SWPC) - National Oceanic and Atmospheric Administration (NOAA) https://www.swpc.noaa.gov/products/solar-cycle-progression, respectively. The monthly observed data for the Smoothed Sunspot Number (SSN), smoothed T-index, and smoothed solar radio flux (F10.7) for the two solar cycles 23 and 24 are presented in Table 1.

Table 1: The monthly-observed data for Smoothed Sunspot Number (SSN), smoothed T-index, and smoothed solar radio flux (F10.7) of solar cycles 23 and 24

Monthly Smoothed Sunspot Number (23)												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1996								11.2	11.3	12.0	13.4	14.3
1997	14.5	15.2	18.3	22.0	24.4	27.2	30.4	33.6	38.2	43.1	47.1	52.0
1998	58.4	65.4	72.0	76.9	80.8	85.4	89.8	93.5	96.4	98.2	102.3	110.4
1999	118.4	122.5	122.3	125.0	132.6	136.3	138.1	142.9	150.5	159.3	164.1	164.0
2000	166.1	170.6	174.3	175.2	172.9	172.7	174.2	172.8	168.8	165.3	163.1	162.7
2001	158.3	152.5	155.1	160.7	163.7	167.4	172.0	175.8	177.1	177.3	180.3	179.1
2002	177.6	179.7	178.2	174.4	171.3	166.9	161.5	155.4	149.5	143.9	136.0	131.4
2003	129.6	125.7	118.7	111.9	107.0	101.7	96.0	92.9	91.8	89.1	86.9	84.1
2004	80.1	76.4	73.2	71.0	69.5	67.1	64.8	63.0	60.2	57.9	56.6	55.7
2005	54.5	53.2	52.3	49.3	45.0	44.5	44.6	41.9	39.4	38.9	38.4	36.0
2006	33.0	29.7	27.4	27.0	27.4	26.2	25.0	25.9	26.0	23.7	21.1	20.2
2007	19.8	19.0	17.7	16.4	14.4	12.8	11.6	9.9	9.6	9.9	9.2	7.9
2008	6.6	5.6	5.1	5.1	5.4	4.8	4.0	3.8	3.2	2.4	2.3	
Monthly Smoothed T-index (23)												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1996								5.0	5.0	3.0	7.0	13.0
1997	14.0	15.0	13.0	12.0	13.0	10.0	10.0	17.0	32.0	28.0	31.0	37.0
1998	41.0	44.0	49.0	59.0	51.0	59.0	81.0	78.0	88.0	74.0	79.0	93.0
1999	97.0	88.0	95.0	82.0	107.0	127.0	123.0	110.0	92.0	98.0	123.0	117.0
2000	110.0	126.0	157.0	149.0	130.0	133.0	148.0	141.0	120.0	127.0	132.0	135.0
2001	132.0	133.0	135.0	126.0	114.0	137.0	111.0	118.0	142.0	150.0	155.0	154.0
2002	171.0	172.0	161.0	140.0	135.0	118.0	110.0	123.0	129.0	106.0	107.0	115.0
2003	105.0	95.0	86.0	82.0	70.0	71.0	76.0	68.0	62.0	63.0	68.0	69.0
2004	59.0	61.0	60.0	58.0	52.0	52.0	51.0	55.0	52.0	51.0	46.0	41.0
2005	42.0	43.0	41.0	34.0	36.0	34.0	38.0	33.0	28.0	21.0	18.0	27.0
2006	26.0	23.0	14.0	23.0	23.0	14.0	17.0	6.0	14.0	5.0	10.0	13.0
2007	20.0	16.0	11.0	9.0	9.0	10.0	7.0	1.0	0.0	-2.0	-7.0	-1.0
2008	6.0	4.0	6.0	2.0	-5.0	-11.0	-6.0	-7.0	-5.0	-9.0	-8.0	
Monthly Smoothed F10.7 cm Solar Radio Flux (23)												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1996								72.2	72.1	72.0	71.9	72.0
1997	72.3	72.7	73.4	74.4	75.7	77.4	79.6	82.2	85.4	90.4	94.1	97.7
1998	101.3	104.9	108.5	112.1	115.6	119.0	122.5	125.8	129.1	132.3	135.5	138.6
1999	141.6	144.5	147.3	150.0	152.6	155.1	157.4	159.7	161.8	164.2	168.0	171.4
2000	174.5	177.2	179.6	181.7	183.4	184.9	186.0	186.9	187.6	188.0	188.1	188.1
2001	187.8	187.3	186.6	185.8	184.7	183.5	182.2	180.7	179.1	177.4	175.5	173.6
2002	171.6	169.4	167.2	164.9	162.6	160.2	157.8	155.3	152.8	150.2	147.6	145.1
2003	142.5	139.9	137.3	134.7	132.2	129.6	127.1	124.6	122.2	119.7	117.4	115.0
2004	112.7	110.5	108.3	106.2	104.1	102.1	100.2	98.3	97.7	96.4	95.1	93.8
2005	92.6	91.4	90.3	89.2	88.2	87.2	86.3	85.3	84.4	83.6	82.8	82.0
2006	81.3	80.5	79.8	79.2	78.6	77.9	77.4	76.8	76.3	75.7	75.2	74.8
2007	74.3	73.8	73.4	73.0	72.6	72.2	71.8	71.4	71.1	70.7	70.3	70.0
2008	69.6	69.3	68.9	68.6	68.2	67.9	67.5	67.2	66.8	66.4	66.0	

Monthly Smoothed Sunspot Number (24)												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2008												2.2
2009	2.5	2.7	2.9	3.3	3.5	4.1	5.5	7.4	9.5	10.9	11.7	12.7
2010	14.0	16.1	18.5	20.8	23.1	24.6	25.2	26.4	29.5	34.5	39.1	42.5
2011	45.7	48.8	53.8	61.1	69.3	77.2	83.6	86.3	86.6	87.4	89.4	92.5
2012	95.5	98.1	98.3	95.1	90.9	86.6	84.5	85.1	85.3	85.8	87.7	88.1
2013	86.8	86.1	84.4	84.3	87.0	90.9	94.6	99.0	104.6	107.0	106.9	107.6
2014	109.3	110.5	114.3	116.4	115.0	114.1	112.6	108.3	101.9	97.3	94.7	92.2
2015	89.3	86.1	82.1	78.9	76.1	72.1	68.3	66.4	65.9	64.3	61.2	57.8
2016	54.4	52.5	50.4	47.8	44.8	41.5	38.5	36.0	33.2	31.5	29.9	28.5
2017	27.8	26.5	25.7	24.8	23.3	22.2	21.0	19.6	18.3	16.7	15.4	15.1
2018	14.2	12.6	9.9	7.8	7.5	7.2	7.0	6.7	6.5	6.8	6.7	6.0
2019	5.4	5.0	4.6	4.3	3.9	3.7	3.5	3.4	3.1	2.6	2.0	
Monthly Smoothed T-index (24)												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2008												-9.0
2009	-2.0	-1.0	-2.0	0.0	2.0	-3.0	-4.0	-7.0	-2.0	-3.0	-3.0	-2.0
2010	12.0	28.0	31.0	21.0	13.0	7.0	18.0	24.0	29.0	20.0	19.0	23.0
2011	22.0	32.0	51.0	63.0	53.0	48.0	44.0	49.0	65.0	85.0	102.0	92.0
2012	81.0	65.0	64.0	69.0	77.0	74.0	70.0	80.0	86.0	75.0	65.0	65.0
2013	74.0	62.0	69.0	84.0	92.0	82.0	81.0	76.0	68.0	76.0	86.0	90.0
2014	91.0	108.0	130.0	114.0	96.0	84.0	86.0	81.0	90.0	94.0	98.0	103.0
2015	92.0	101.0	91.0	97.0	85.0	79.0	71.0	48.0	40.0	43.0	53.0	50.0
2016	52.0	57.0	46.0	30.0	34.0	28.0	26.0	25.0	28.0	17.0	12.0	10.0
2017	14.0	19.0	11.0	8.0	2.0	2.0	0.0	3.0	16.0	13.0	5.0	6.0
2018	8.0	2.0	3.0	-2.0	-6.0	-3.0	-3.0	-8.0	-6.0	-10.0	-15.0	-9.0
2019	-5.0	-3.0	-4.0	-4.0	-9.0	-14.0	-12.0	-14.0	-11.0	-13.0	-15.0	
Monthly Smoothed F10.7 cm Solar Radio Flux (24)												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2008												68.4
2009	68.6	68.8	69.0	69.3	69.7	70.2	71.0	72.1	73.3	74.1	74.5	74.8
2010	75.5	76.4	77.4	78.2	79.0	79.6	80.0	80.5	82.6	85.9	88.4	90.3
2011	91.9	93.4	96.6	101.2	106.5	111.8	116.4	119.0	119.2	118.8	119.9	122.0
2012	124.9	127.2	127.3	126.3	124.3	121.6	119.9	119.4	119.1	119.5	120.4	120.4
2013	119.1	118.1	117.2	116.7	118.3	121.1	124.3	128.5	132.9	135.3	136.0	136.5
2014	137.9	139.2	141.4	144.2	145.4	146.1	145.7	143.0	140.4	138.8	137.8	137.6
2015	136.6	134.6	131.9	127.9	123.9	120.0	116.5	113.9	111.3	108.4	105.8	102.7
2016	99.9	98.2	96.7	95.4	93.3	90.5	87.8	85.6	83.8	82.6	81.2	80.1
2017	79.5	78.8	78.9	78.8	78.1	77.7	77.2	76.7	76.2	75.5	74.9	74.7
2018	74.3	73.6	72.1	70.7	70.2	70.0	70.0	70.0	70.1	70.4	70.5	70.3
2019	70.0	69.9	69.8	69.7	69.6	69.7	69.8	69.8	69.8	69.6	69.4	

In this work, the annual average variations for the monthly smoothed observed values of the tested solar-ionospheric indices (SSN, T-Index, and F10.7 cm) have been calculated for the periods (Aug.1996 - Nov.2008) and (Dec. 2008 - Nov. 2019) of the 23^{rd} and 24^{th} solar cycles, respectively. Table 2 presents the annual average dataset values of the three indices over the chosen periods of time. The annual average values for the year 1996 were adopted for a period of five months only, due to the (23^{rd}) solar cycle that began in (August 1996) and therefore the first year of the cycle (1996) extended for five months only (August - December).

Table 2: The annual average observed data for SSN, T-index, and F10.7 for solar cycles (23, 24).

Annual Average (Obs.) of Solar Cycle (23)				Annual Average (Obs.) of Solar Cycle (24)			
Year	SSN	T-index	F10.7	Year	SSN	T-index	F10.7
1996*	12.4	6.6	72.0	2009	6.4	-2.3	71.3
1997	30.5	19.3	81.3	2010	26.2	20.4	81.2
1998	85.8	66.3	120.4	2011	73.5	58.8	109.7
1999	139.7	104.9	156.1	2012	90.1	72.6	122.5
2000	169.9	134.0	183.8	2013	94.9	78.3	125.3
2001	168.3	133.9	182.0	2014	107.2	97.9	141.5
2002	160.5	132.3	158.7	2015	72.4	70.8	119.5
2003	103.0	76.3	128.5	2016	40.8	30.4	89.6
2004	66.3	53.2	102.1	2017	21.4	8.3	77.3
2005	44.8	32.9	86.9	2018	8.2	-4.1	71
2006	26.1	15.7	77.8	2019	3.8	-9.5	69.7
2007	13.2	6.1	72.05				
2008	4.4	-3.0	67.86				

The annual average behavior of the SSN, T-index, and F10.7 indices for the studied years are illustrated in Figure 1.

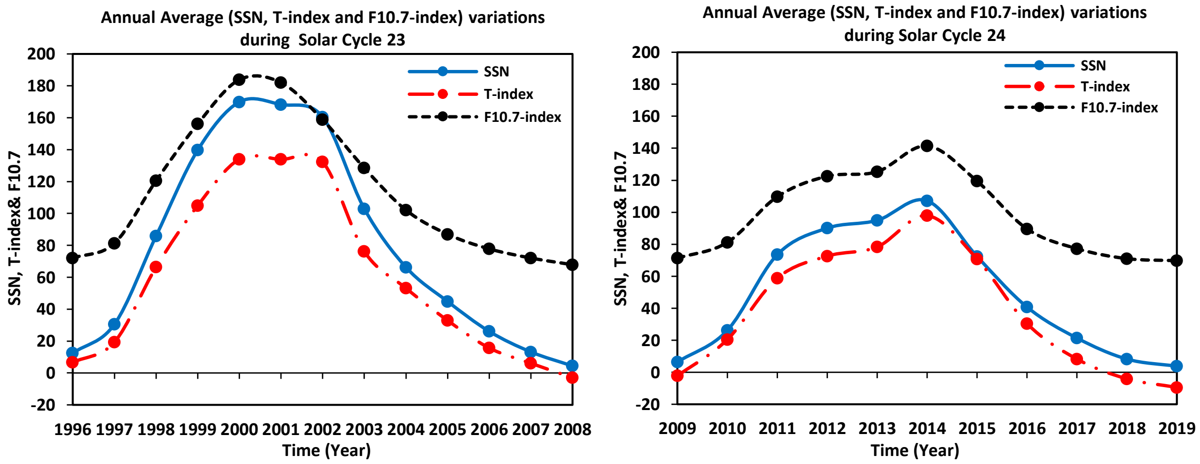


Figure 1: The annual average behavior of the SSN, T-index, and F10.7 indices during the studied years of solar cycles 23 and 24.

In this research, the correlative conduct between the studied indices have been evaluated for the studied periods (1996-2008) and (2008-2019) of the 23rd and 24th solar cycles, respectively. Figures (2) & (3) illustrate the correlation between the annual average values for each of the three tested indices corresponding to the others for solar cycles 23 and 24, respectively: (SSN Vs. T-index), (SSN Vs. F10.7), (T-index Vs. F10.7), (T-index Vs. SSN), (F10.7 Vs. SSN), (F10.7 Vs. T-index).

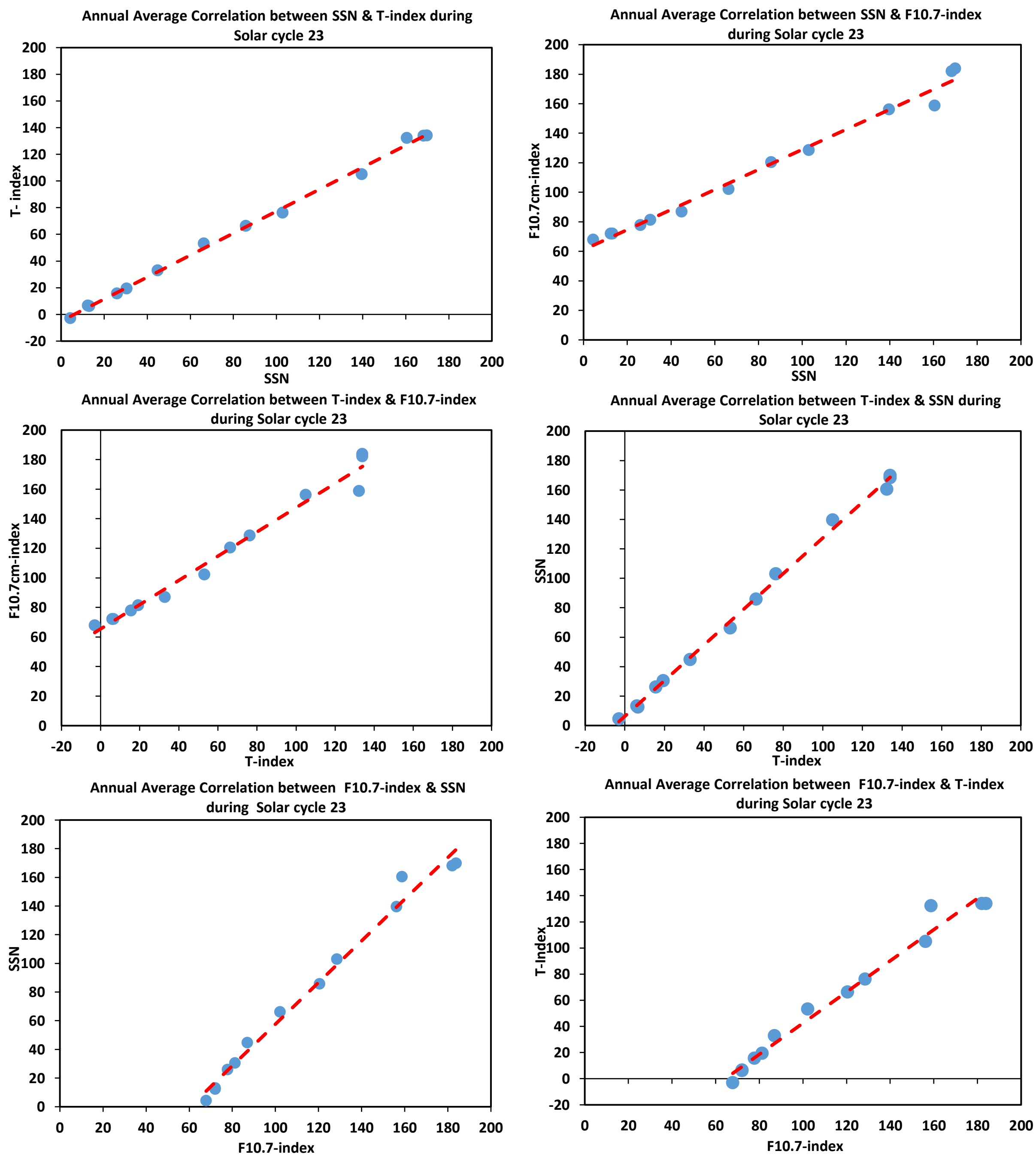


Figure 2: The correlation between the annual average values of the SSN, T-index, and F10.7 indices during solar cycle 23.

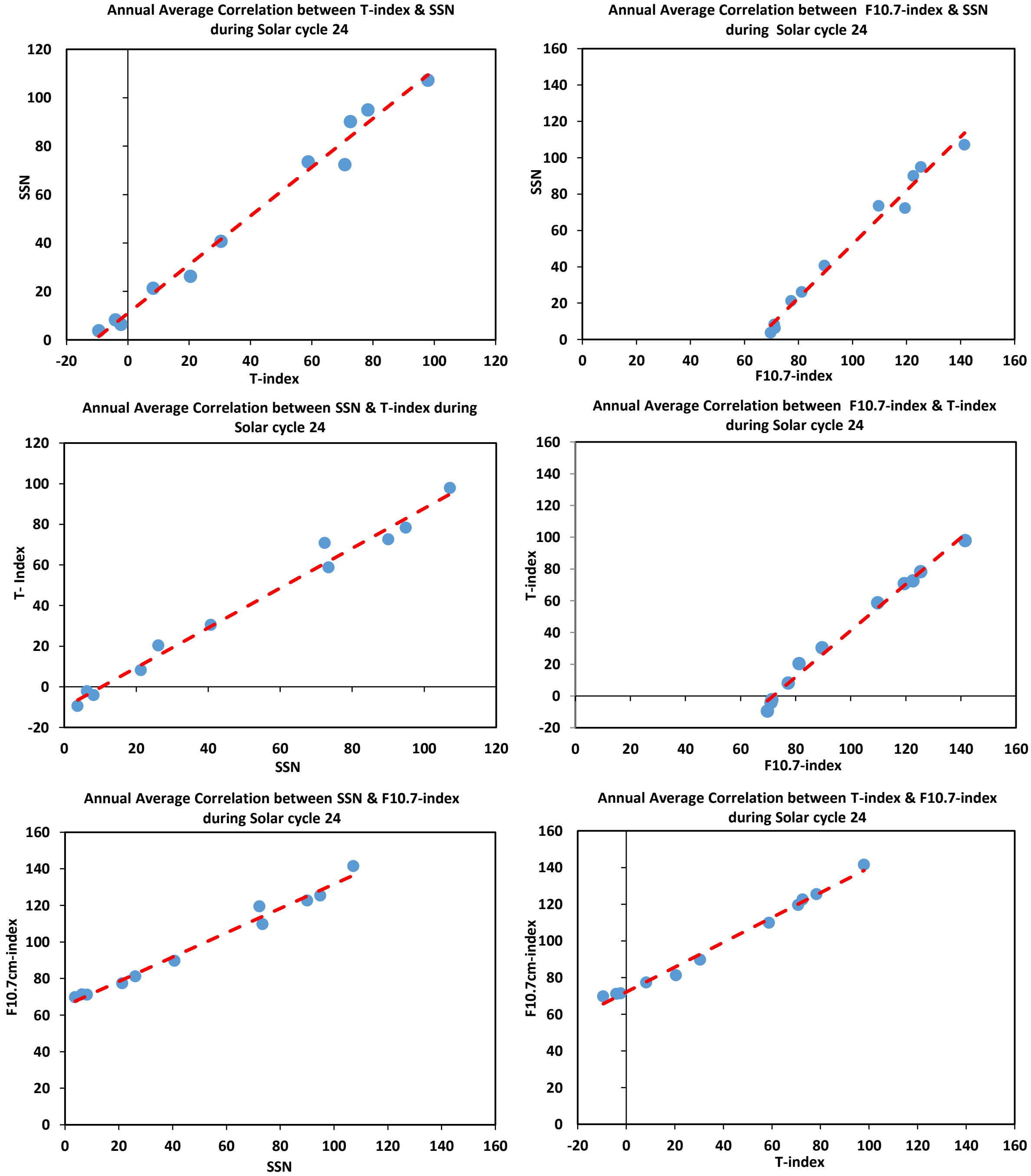


Figure 3: The correlation between the annual average values of the SSN, T-index, and F10.7 indices during solar cycle 24.

Depending on the results of the correlative relationships for the annual average between SSN, T-index and F10.7cm indices of solar cycles 23 and 24, the mathematical correlative equation between the tested indices has been suggested as a polynomial equation. The suggested mathematical correlative equation can be expressed as follows:

$$Y = \sum_{n=0}^{\infty} k_n X^n \qquad \text{.........} (2)$$

$$Y = K_o + K_1 X^1 + K_2 X^2 + K_3 X^3 + \ldots + K_n X^n \qquad \text{.........} (3)$$

So, the suggested mutual correlation formulas between the studied indices can be expressed by a first order polynomial formula (linear regression equation, n = 0, 1) which can be presented by the following set of equations:

$$\left.\begin{aligned} T\text{-}index &= \sum_{n=0}^{\infty} k_n (SSN)^n \\ SSN &= \sum_{n=0}^{\infty} k_n (T\text{-}index)^n \\ F10.7 &= \sum_{n=0}^{\infty} k_n (SSN)^n \\ SSN &= \sum_{n=0}^{\infty} k_n (F10.7)^n \\ F10.7 &= \sum_{n=0}^{\infty} k_n (T\text{-}index)^n \\ T\text{-}index &= \sum_{n=0}^{\infty} k_n (F10.7)^n \end{aligned}\right\} \qquad \text{.........} (4)$$

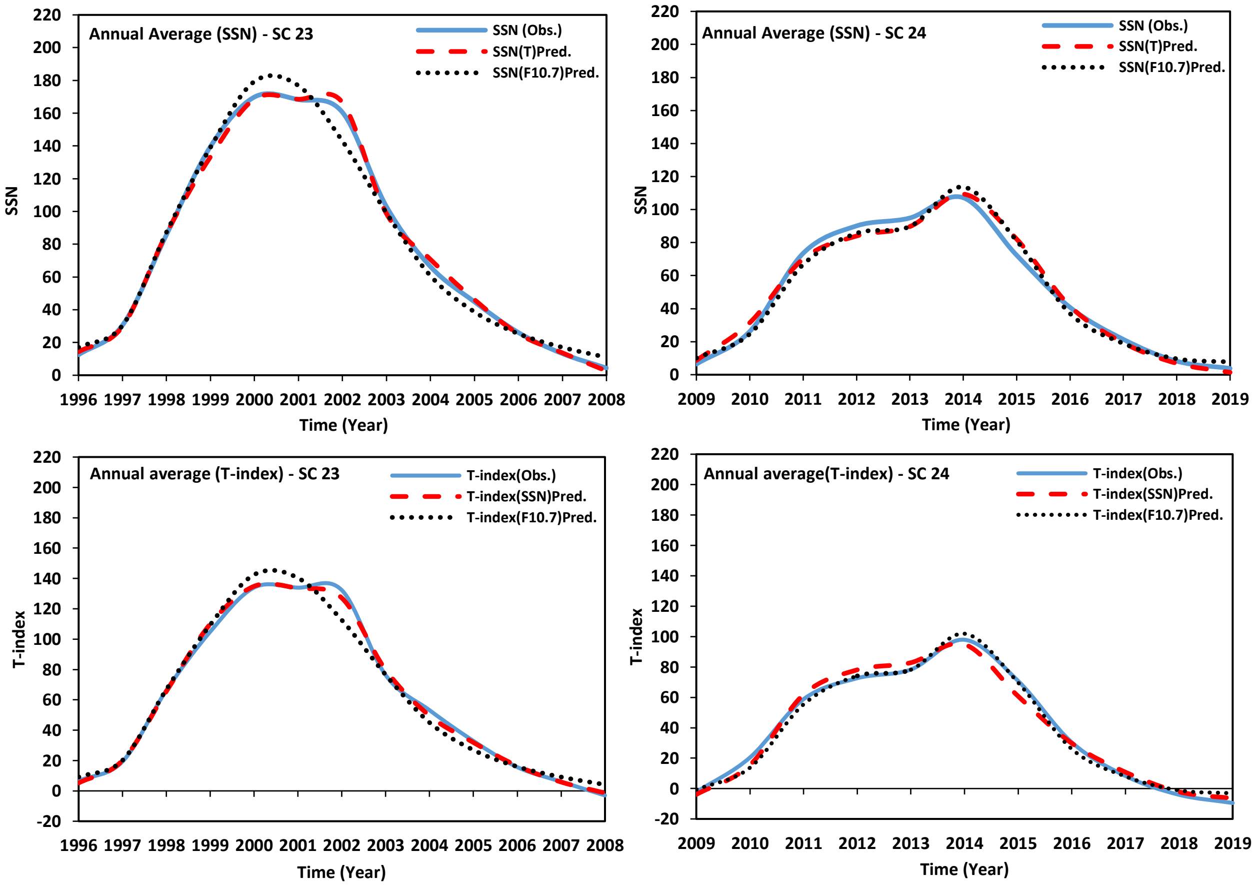
Where (k_n) represents the correlation coefficient for the (n^{th}) order (t.e n=0, 1, 2, ...) of the polynomial equation. The correlation coefficients and determination coefficients of the correlative relationship between the tested sets of the studied indices (SSN & T-index), (SSN & F10.7), (T-index & SSN), (T-index & F10.7), (F10.7 & SSN) and (F10.7 & T-index) for the annual time of the studied periods of solar cycles 23 and 24 have been determined. Table 3 presents the determined values of the correlation coefficients and the determination coefficients between (SSN, T-index & F10.7) of solar cycles 23 and 24.

Table 3: The determined correlation coefficients and determination coefficient values for the annual time between (SSN, T-index & F10.7) indices of solar cycles 23 and 24.

Solar Cycle (23)				
Indices	Correlated Index	Correlation Coefficients		Determination Coefficient (R^2)
		K_0	K_1	
SSN	T-index	-5.0168	0.8233	0.9974
	F10.7	61.057	0.6791	0.9867
T-index	SSN	6.2839	1.2115	0.9974
	F10.7	65.46	0.8205	0.9788
F10.7	SSN	-87.664	1.4529	0.9867
	T-index	-76.813	1.1929	0.9788

Solar Cycle (24)				
Indices	Correlated Index	Correlation Coefficients		Determination Coefficient (R^2)
		K_0	K_1	
SSN	T-index	-10.191	0.980	0.985
	F10.7	65.065	0.666	0.983
T-index	SSN	10.973	1.006	0.985
	F10.7	72.087	0.677	0.990
F10.7	SSN	-95.163	1.476	0.983
	T-index	-105.030	1.462	0.990

The predicted annual average values of the (SSN, T-index, and F10.7) indices that have been generated using the suggested correlative equations between the tested solar-ionospheric indices have been compared with observed annual average values of the tested indices of the solar cycles 23 and 24. Figure 4 shows a comparison between the observed and predicted annual values of the SSN, T-index, and F10.7 indices for the studied periods of solar cycles 23 and 24.



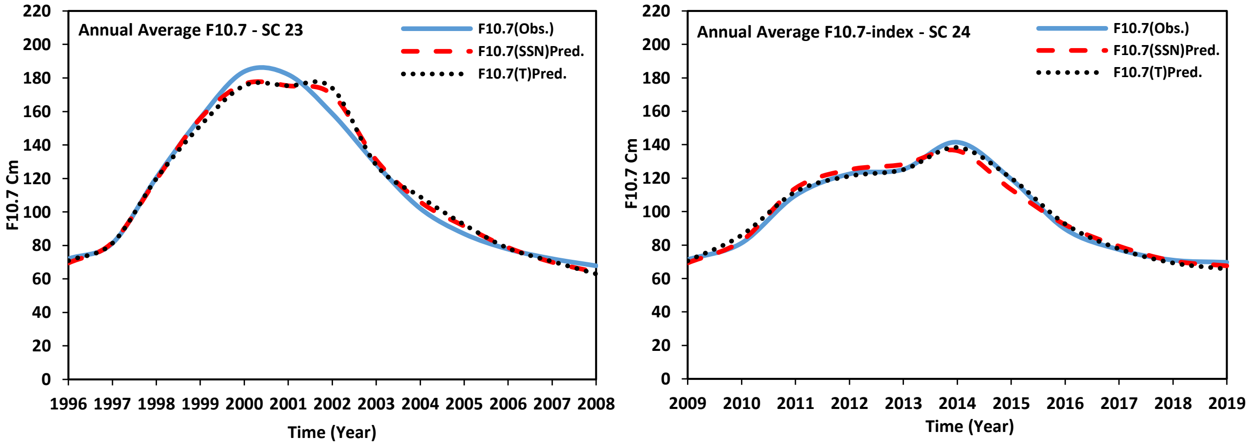


Figure 4: The comparison between the observed and predicted annual values of the SSN, T-index and F10.7 indices for the studied periods of solar cycles 23, 24.

In order to evaluate the annual correlative relationships between the selected solar-ionospheric indices, statistical calculations have been conducted for the observed and predicted values of the tested indices during the tested periods (Aug.1996 - Nov.2008) and (Des. 2008 - Nov. 2019) of solar cycles 23 and 24. The Correlation Coefficient (R), Determination Coefficient (R^2), Normalized Root Mean Square Error (NRMSE), Mean Difference (Mean Diff.), and Normalized Mean Absolute Error (NMAE) statistical analysis methods have been used to conduct the statistical calculations. Table 4 presents the results of the statistical calculations that have been conducted.

Table 4: Statistical calculations results for the observed and predicted values of the annual correlative indices during solar cycles (23, 24)

Statistical Methods of Solar Cycle (23)					
Annual Average	Corr. Coeff. (R)	Det. Coeff. (R^2)	NRMSE	Mean Diff.	NMAE
SSN Vs. T-index	0.999	0.997	0.039	0.001	0.030
SSN Vs. F10.7	0.993	0.987	0.089	-0.001	0.067
T-index Vs. SSN	0.999	0.997	0.043	0.002	0.032
T-index Vs. F10.7	0.989	0.978	0.122	0.004	0.087
F10.7 Vs. SSN	0.993	0.987	0.042	-0.003	0.032
F10.7 Vs. T-index	0.989	0.978	0.053	0.000	0.038
Statistical Methods of Solar Cycle (24)					
Annual Average	Corr. Coeff. (R)	Det. Coeff. (R^2)	NRMSE	Mean Diff.	NMAE
SSN Vs. T-index	0.993	0.985	0.091	-0.025	0.075
SSN Vs. F10.7	0.991	0.982	0.099	0.000	0.089
T-index Vs. SSN	0.993	0.985	0.116	0.027	0.097
T-index Vs. F10.7	0.995	0.990	0.095	0.028	0.077
F10.7 Vs. SSN	0.991	0.982	0.034	0.002	0.029
F10.7 Vs. T-index	0.995	0.990	0.025	-0.020	0.020

Discussion

In this paper, the annual behavior and cross-correlation between three different solar-ionospheric indices (Smoothed Sunspot Number (SSN), Ionospheric T-Index (T-index), and Solar Flux (F10.7)) have been assessed for the periods (Aug.1996 - Nov.2008) and (Dec. 2008 - Nov. 2019) of solar cycles 23 and 24, respectively. The annual average behavior of the tested indices, which were presented in Figure 1, showed that the three indices displayed almost a similar annual behavior during the tested times of solar cycles 23 and 24. The results of the evaluation of the annual correlative conduct between the studied indices which were illustrated in Figures 2 and 3, showed that the correlative relationship between the studied indices: (SSN Vs. T-index), (SSN Vs. F10.7), (T-index Vs. F10.7), (T-index Vs. SSN), (F10.7 Vs. SSN), (F10.7 Vs. T-index) can be represented by a simple first order polynomial formula (linear regression equation). According to this evaluation, a set of mathematical mutual correlative equations have been suggested. The comparison of the annual predicted values that were calculated using the suggested mathematical correlative equations, which were presented in Figure 4, showed a similar and close behavior to that of the observed annual average values of the tested indices of solar cycles 23 and 24. The evaluation for the nature of the annual correlative relationships between the tested indices have been made by conducting statistical calculations for the calculated datasets of the tested indices. The statistical calculation results of the correlation coefficient (R), determination coefficient (R^2), normalized root mean square error (NRMSE), mean difference (Mean Diff.), and normalized mean absolute error (NMAE), which were presented in Table 4, showed good results for all statistical parameters.

Conclusions

According to the above discussion, the conclusions can be summarized as follows:

1. The annual average variation of the tested indices showed a similar behavior of the three examined indices during tested years of solar cycles 23 and 24.
2. The values of the (SSN, T-index, and F10.7) indices during the maximum years of solar cycle 23 were higher than their values during the maximum years of solar cycle 24.
3. The annual cross-correlation relationships between the studied indices are simple and can be represented by a first order polynomial formula “linear regression equation”.
4. The calculated values using the suggested mutual correlation equations gave a good fit with the observed annual average values of the tested indices during solar cycles 23 and 24.
5. The statistical calculation results of the calculated datasets of the tested indices showed very good results for all statistical parameters.
6. The evaluation of the annual correlation between solar-ionospheric indices during solar cycles 23 and 24 reveals that the tested indices are mutually and linearly correlated to each other and can be predicted reciprocally depending on the suggested mathematical cross-correlation equations during the studied time periods.

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