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Comparative Analysis for the Seasonal Variations of the IF2 and T Ionospheric Indices during Solar Cycles 23 and 24

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Abstract

In this work, a comparative analysis for the behavior and pattern of the variations of the IF2 and T Ionospheric indices was conducted for the minimum and maximum years of solar cycles 23 and 24. Also, the correlative relationship between the two ionospheric indices was examined for the seasonal periods spanning from August 1996 to November 2008 for solar cycle 23 and from December 2008 to November 2019 for solar cycle 24. Statistical calculations were performed to compare predicted values with observed values for the selected indices during the tested timeframes. The study's findings revealed that the behavior of the examined indices exhibited almost similar variations throughout the studied timeframe. The seasonal variations were adopted to examine the cross-correlation between the studied indices. The seasonal correlation between tested indices demonstrated that the two indices are highly correlated to each other, with determination coefficient (R^2) values ranging from 0.991 to 0.998 during solar cycle 23 and from 0.996 to 0.998 during solar cycle 24. Furthermore, the results of the comparative analytical study revealed that the mathematical correlation equation between the tested indices could be described as a first-order polynomial equation. The proposed mathematical correlation formula for these two indices exhibited a high level of accuracy and good fit between observed values and generated datasets for all seasons during both solar cycles 23 and 24.

Keywords: Ionospheric Indices, T-index, IF2-index, Solar Cycle.

مقارنة تحليلية للتغيرات الموسمية لمؤشرات الغلاف الأيوني IF2 و T خلال الدورات الشمسية 23 و 24

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الخلاصة

في هذا العمل، تم إجراء تحليل مقارن لسلوك ونمط التغيرات في مؤشرات الأيونوسفير IF2 و T للسنوات الدنيا والقصوى للدورات الشمسية 23 و 24. كما تم فحص العلاقة الارتباطية بين المؤشرين الأيونوسفيريين من أجل الفترات الموسمية الممتدة من أغسطس 1996 إلى نوفمبر 2008 للدورة الشمسية 23 ومن ديسمبر 2008 إلى نوفمبر 2019 للدورة الشمسية 24. وتم إجراء الحسابات الإحصائية لمقارنة القيم المتوقعة مع القيم المرصودة للمؤشرات المختارة خلال الأطر الزمنية التي تم اختبارها. كشفت نتائج الدراسة أن سلوك المؤشرات

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التي تم فحصها أظهر اختلافات متشابهة تقريبًا طوال الإطار الزمني المدروس. تم اعتماد التغيرات الموسمية لفحص الارتباط المتبادل بين المؤشرات المدروسة. أظهرت العلاقة الموسمية بين المؤشرات المختبرة أن المؤشرين يرتبطان ارتباطاً وثيقاً ببعضهما البعض، حيث تتراوح قيم معامل التحديد (R^2) من 0.991 إلى 0.998 خلال الدورة الشمسية 23 ومن 0.996 إلى 0.998 خلال الدورة الشمسية 24. علاوة على ذلك، كشفت نتائج الدراسة التحليلية المقارنة أن معادلة الارتباط الرياضي بين الدلائل المختبرة يمكن وصفها بأنها معادلة متعددة الحدود من الدرجة الأولى. أظهرت صيغة الارتباط الرياضي المقترحة لهذين المؤشرين مستوى عاليًا من الدقة والتوافق الجيد بين القيم المرصودة ومجموعات البيانات التي تم أنشاؤها لجميع الفصول خلال الدورتين الشمسيتين 23 و24.

1. Introduction

The ionosphere constitutes the uppermost layer of Earth's atmosphere and it's formed due to the ionization process that occurs in the upper atmosphere by the solar electromagnetic radiation, spanning from approximately 60 kilometers above the Earth's surface to altitudes exceeding 1000 kilometers, where it gradually merges with the near-earth outer space [1]. Solar radiation, encompassing a broad spectrum of wavelengths emitted by the sun, traverses' space and reaches the outermost layers of the atmosphere [2]. In these regions, particularly in the presence of X-rays and ultraviolet, the intense energy from solar photons is sufficient to ionize the present molecules and atoms [3, 4]. When a photon collides with a molecule or atom, it imparts its energy to an electron, endowing it with additional kinetic energy. Under specific conditions, when this surplus energy surpasses the binding energy of the atom or molecule, it expels the electron from its confines, resulting in ionization and the creation of positively charged ions along with free electrons. Therefore, based on the altitude and density distribution of ions the ionosphere is divided into three distinct regions, namely D, E, and F [5, 6]. The extent of ionization varies with altitude throughout the ionosphere, given that the intensity of radiation diminishes with decreasing altitude. Consequently, the density of gases in this region undergoes alterations as altitude changes. The ionization level within the ionosphere experiences fluctuations influenced by factors such as time of day, seasonal variations, and external influences like solar activity [7]. The sun's radiant emissions lead to the formation of positive ions and free electrons from molecular and atomic constituents. Conversely, when a negatively charged electron collides with a positively charged ion, they may recombine [8]. As a result, two opposing effects of charge separation and recombination are occurring. This is referred to as a condition of dynamic equilibrium.

Hence, the level of ionization is determined by the rate of "ionization" and "recombination" processes [9, 10]. Consequently, the ionospheric indices are utilized extensively and are highly recommended for usage in ionospheric long-term research and forecasting. Over the past decades, numerous ionospheric indices have been proposed with the aim of enhancing the accuracy of ionospheric condition predictions. These include the MF2 index, the Ionospheric T-Index, the ionospheric activity index, denoted as the IG index, and the IF2 index, which assesses the ionization of the F2 layer. Due to the F layer being highly sensitive to variations in solar activity, ionospheric indices stand as valuable and significant metrics [11]. In this investigation, the IF2-index and T-index, both have been chosen for evaluation.

The IF2-Index, which stands as the inaugural ionospheric activity index, was formulated by directly comparing solar indices with ionospheric measurements to gauge ionospheric activity levels. This comparison was made to establish the level of ionospheric activity by utilizing monthly mean data from two sources: the Zurich sunspot number and the monthly mean noon F2-critical frequency (f_oF2) values acquired at three distinct ionospheric stations [12]. The IF2 measurement is dependent on variations in both solar activity and the ionization of the F2 layer, and its data are updated monthly [13]. Due to their superior ability to represent solar cycle variations in ionospheric parameters, the IF2, IG, and T-indices were adopted by the International Radio Consultative Committee (CCIR) as fundamental indices for ionospheric propagation. Consequently, their monthly values have been consistently published in the Telecommunication Journal [14].

The T-index is a measure of the highest frequencies that can be refracted from certain ionosphere layer. To determine the index value, Ionogram readings of foF2 within the ionosphere are employed. The range of signal frequencies that can be reflected from the ionosphere is contingent upon solar activity levels. Typically, the number of sunspots serves as a gauge for solar activity, with a general rule being that higher sunspot numbers correspond to the higher frequencies that may reflected from the ionosphere. Variations in the ionosphere are also influenced by factors like time of day, season, and geographical location. Consequently, the Australian Ionospheric Prediction Service (IPS) developed the T-index [15, 16]. This index is derived based on data gathered from ionosondes, which essentially function as radar systems for scanning the ionosphere. The highest frequency reflected by the ionosphere, often denoted as f_oF2, essentially represents the Maximum Usable Frequency (MUF) for a particular communication circuit. The T-index is determined by this process, although it becomes more complex due to the need to repeat it for each time of day and every month of the year. Additionally, the diverse points on Earth necessitate the creation of maps to account for regional variations. The T-index can take on a wide range of values but typically falls within the range (-50 to 200). During periods of low solar activity, characterized by lower T-index values, lower (HF) frequencies are preferable. Conversely, as the solar cycle approaches its maximum or during severe ionospheric storms, the T-index tends to be higher, and as a result, frequencies will typically be higher as well [17]. Several studies and research have been performed related to the investigation of ionospheric indices and their effects on the Earth's atmosphere generally and the ionosphere layer especially. In 1968, Muggleton, L. M., et al. delved into the relationship between sunspot numbers and the ionospheric index IF2. Their results unveiled a predictable pattern of change in the connection between R and IF2 across solar cycles, with this connection relying on the passage of time. It is likely that this trend will continue to oscillate [18]. In 2021, Thabit, S.A., et al. determined the annual optimal reliable frequency for transmitter/receiver sites in Iraq. Their calculations were based on T-index values, and the findings indicate that the ORF ionospheric parameter increases as the distance (path length) between transmitting and receiving stations grows, and it also varies with bearing [19].

2. Test and Analysis Results

In the present work, a comparative analytical study has been conducted between IF2 and T ionospheric Indices. The comparative analysis was made to investigate the behavior and pattern of the variations of the tested ionospheric indices during the minimum and maximum years (1996, 2001) (2009, 2014) of solar cycles 23 and 24, respectively. The monthly observed dataset of the IF2-index was acquired from the UK Solar System Data Centre (UKSSDC) https://www.ukssdc.ac.uk/cgi-bin/wdcc1/secure/geophysical_parameters.pl, whereas the values of the T-index were obtained from the IPS Radio and Space Services, Ionospheric Prediction Services (IPS), Australian Space Weather Forecasting Center (ASWFC) (formally, known as Space Weather Services (SWS), https://www.sws.bom.gov.au/HF_Systems/6/4/1. Table (1) present the monthly observed values of the IF2 and T-Index for solar cycles 23 and 24, respectively.

Table 1: Monthly-observed data of the IF2 and T-Index for solar cycles 23 and 24

Monthly IF2, SC. (23) - (Aug. 1996 - Nov. 2008)													
Month	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**
Jan		-14.7	25.8	98.5	96.1	107.7	149.4	106.6	43.3	17.2	6.6	-1.0	-5.4
Feb		-0.6	27.5	78.1	119.6	115.0	153.7	87.3	47.8	30.8	14.0	4.9	-9.8
Mar		2.1	44.4	93.5	151.2	133.8	168.3	78.1	48.2	33.3	5.6	3.5	3.3
Apr		-3.7	54.8	95.9	156.8	137.0	141.7	91.4	52.5	28.0	12.6	-2.4	-3.0
May		-1.8	36.8	97.0	144.2	115.3	141.4	64.2	41.5	23.4	8.9	1.4	-26.1
Jun		-12.5	55.5	115.7	133.1	133.2	117.3	61.9	43.6	27.6	0.2	2.0	-16.2
Jul		7.5	66.1	119.4	149.8	105.6	110.7	70.6	40.0	31.5	15.0	6.1	-10.5
Aug	-7.7	10.5	66.2	118.3	156.1	116.9	130.0	61.4	47.3	31.7	6.9	-4.6	-14.8
Sep	-14.3	24.3	83.7	115.1	137.4	161.7	156.5	66.0	42.2	23.4	1.4	-14.7	-23.2
Oct	-34.6	2.9	89.2	116.6	155.7	164.2	136.5	60.0	43.6	4.9	-17.5	-33.7	-31.0
Nov	-23.9	20.0	86.9	132.7	144.9	160.8	112.6	62.4	30.7	-0.5	-21.0	-45.3	-56.4
Dec	-16.8	24.6	108.5	138.4	160.4	175.5	129.2	61.7	24.2	12.3	-25.0	-40.4	

Monthly T-index SC. (23) - (Aug. 1996 - Nov. 2008)													
Month	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**
Jan		14.0	41.0	97.0	110.0	132.0	171.0	105.0	59.0	42.0	26.0	20.0	6.0
Feb		15.0	44.0	88.0	126.0	133.0	172.0	95.0	61.0	43.0	23.0	16.0	4.0
Mar		13.0	49.0	95.0	157.0	135.0	161.0	86.0	60.0	41.0	14.0	11.0	6.0
Apr		12.0	59.0	82.0	149.0	126.0	140.0	82.0	58.0	34.0	23.0	9.0	2.0
May		13.0	51.0	107.0	130.0	114.0	135.0	70.0	52.0	36.0	23.0	9.0	-5.0
Jun		10.0	59.0	127.0	133.0	137.0	118.0	71.0	52.0	34.0	14.0	10.0	-11.0
Jul		10.0	81.0	123.0	148.0	111.0	110.0	76.0	51.0	38.0	17.0	7.0	-6.0
Aug	5.0	17.0	78.0	110.0	141.0	118.0	123.0	68.0	55.0	33.0	6.0	1.0	-7.0
Sep	5.0	32.0	88.0	92.0	120.0	142.0	129.0	62.0	52.0	28.0	14.0	0.0	-5.0
Oct	3.0	28.0	74.0	98.0	127.0	150.0	106.0	63.0	51.0	21.0	5.0	-2.0	-9.0
Nov	7.0	31.0	79.0	123.0	132.0	155.0	107.0	68.0	46.0	18.0	10.0	-7.0	-8.0
Dec	13.0	37.0	93.0	117.0	135.0	154.0	115.0	69.0	41.0	27.0	13.0	-1.0	

Monthly IF2 SC. (24) - (Dec. 2008 - Nov. 2019)											
Month	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
Jan		-25.8	-5.7	11.5	62.6	71.8	70.4	88.4	34.8	-7.0	-12.0	-22.1
Feb		-11.7	19.4	8.9	58.6	59.4	100.4	93.4	42.3	6.8	-7.8	-23.8
Mar		-10.2	24.9	41.6	54.5	57.3	126.7	84.9	41.6	4.4	-1.7	-16.1
Apr		-9.5	6.9	61.9	65.7	75.2	108.5	92.1	20.9	3.3	-9.4	-17.1
May		-10.5	8.8	41.1	66.9	87.7	89.6	86.4	20.8	-5.4	-14.4	-16.6
Jun		-7.8	2.0	39.5	72.8	71.8	64.6	64.5	15.8	0.5	-7.3	-18.5
Jul		-8.0	12.0	40.3	62.4	70.1	85.6	56.5	22.2	-0.7	-6.0	-6.0
Aug		-11.9	27.0	44.4	73.7	76.3	69.3	44.9	27.3	6.7	-5.3	-13.6
Sep		-20.3	14.2	64.0	91.2	65.3	97.0	34.6	25.9	14.3	-19.2	-26.5
Oct		-27.4	-2.6	97.7	87.6	86.0	109.7	42.4	9.3	-3.5	-36.2	-35.2
Nov		-36.6	-11.0	123.3	75.6	99.8	113.3	35.6	-17.4	-26.5	-55.9	-47.8
Dec	-39.8	-29.4	-7.7	108.3	54.7	99.4	106.3	34.9	-14.5	-38.2	-45.5	

Monthly T-index SC. (24) - (Dec. 2008 - Nov. 2019)												
Month	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
Jan		-2.0	12.0	22.0	81.0	74.0	91.0	92.0	52.0	14.0	8.0	-5.0
Feb		-1.0	28.0	32.0	65.0	62.0	108.0	101.0	57.0	19.0	2.0	-3.0
Mar		-2.0	31.0	51.0	64.0	69.0	130.0	91.0	46.0	11.0	3.0	-4.0
Apr		0.0	21.0	63.0	69.0	84.0	114.0	97.0	30.0	8.0	-2.0	-4.0
May		2.0	13.0	53.0	77.0	92.0	96.0	85.0	34.0	2.0	-6.0	-9.0
Jun		-3.0	7.0	48.0	74.0	82.0	84.0	79.0	28.0	2.0	-3.0	-14.0
Jul		-4.0	18.0	44.0	70.0	81.0	86.0	71.0	26.0	0.0	-3.0	-12.0
Aug		-7.0	24.0	49.0	80.0	76.0	81.0	48.0	25.0	3.0	-8.0	-14.0
Sep		-2.0	29.0	65.0	86.0	68.0	90.0	40.0	28.0	16.0	-6.0	-11.0
Oct		-3.0	20.0	85.0	75.0	76.0	94.0	43.0	17.0	13.0	-10.0	-13.0
Nov		-3.0	19.0	102.0	65.0	86.0	98.0	53.0	12.0	5.0	-15.0	-15.0
Dec	-9.0	-2.0	23.0	92.0	65.0	90.0	103.0	50.0	10.0	6.0	-9.0	

Also, the monthly variations of the tested indices during the maximum and minimum years of solar cycles 23 and 24 are shown in Figure (1).

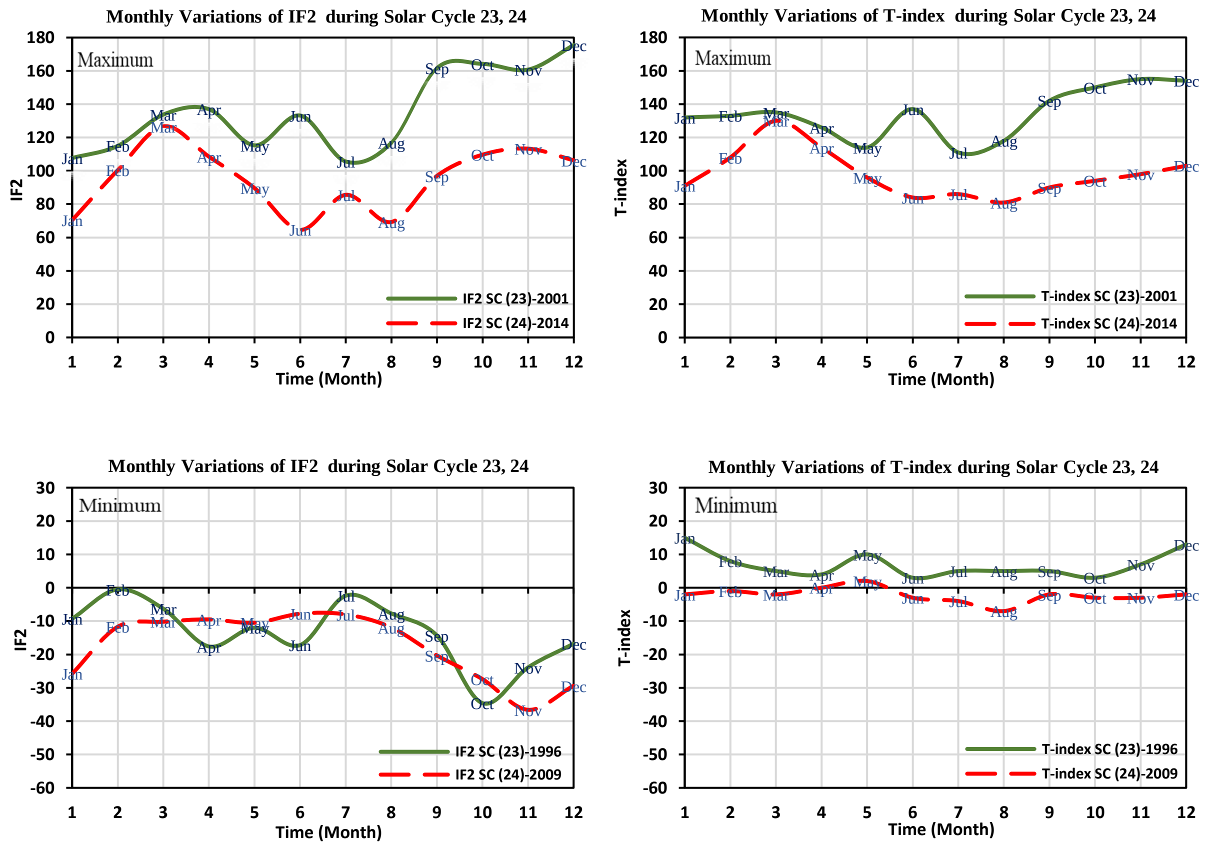


Figure 1: Monthly behavior of IF2 and T indices during the minimum and maximum years (1996, 2001) and (2009, 2014) of solar cycles 23 and 24.

Based on the monthly datasets of the two indices during the selected periods of time shown in Table (1) and their monthly behavior presented in Figure (1), The monthly behavior of the studied indices showed fluctuating behavior over particular monthly periods, especially during the months of the minimum years of the tested cycles, which may be due to seasonal variations, that affected the normal behavior of the two indices during those periods. Accordingly, in this research, the seasonal variations were adopted to examine the correlation relationships between the studied indices. Table (2) displays the values of the seasonal average datasets for the two indices during the 23rd and 24th solar cycles, respectively.

Table 2: Seasonal average values of the two indices during solar cycles 23 and 24

Seasonal Average Variations (IF2) SC (23)					Seasonal Average Variations (T-index) SC (23)				
Year	**Winter**	**Spring**	**Summer**	**Autumn**	**Year**	**Winter**	**Spring**	**Summer**	**Autumn**
1996				-24.3	**1996**				5.0
1997	-10.7	-1.1	1.8	15.7	**1997**	14.0	12.7	12.3	30.3
1998	26.0	45.3	62.6	86.6	**1998**	40.7	53.0	72.7	80.3
1999	95.0	95.5	117.8	121.5	**1999**	92.7	94.7	120.0	104.3
2000	118.0	150.7	146.3	146.0	**2000**	117.7	145.3	140.7	126.3
2001	127.7	128.7	118.6	162.2	**2001**	133.3	125.0	122.0	149.0
2002	159.5	150.5	119.3	135.2	**2002**	165.7	145.3	117.0	114.0
2003	107.7	77.9	64.6	62.8	**2003**	105.0	79.3	71.7	64.3

2004	50.9	47.4	43.6	38.8
2005	24.1	28.2	30.3	9.3
2006	11.0	9.0	7.4	-12.4
2007	-7.0	0.8	1.2	-31.2
2008	-18.5	-8.6	-13.8	-36.9

2004	63.0	56.7	52.7	49.7
2005	42.0	37.0	35.0	22.3
2006	25.3	20.0	12.3	9.7
2007	16.3	9.7	6.0	-3.0
2008	3.0	1.0	-8.0	-7.3

Seasonal Average Variations (IF2) SC (24)				
Year	**Winter**	**Spring**	**Summer**	**Autumn**
2009	-25.8	-10.1	-9.2	-28.1
2010	-5.2	13.5	13.7	0.2
2011	4.2	48.2	41.4	95.0
2012	76.5	62.4	69.6	84.8
2013	62.0	73.4	72.7	83.7
2014	90.1	108.3	73.2	106.7
2015	96.0	87.8	55.3	37.5
2016	37.3	27.8	21.8	5.9
2017	-4.9	0.8	2.2	-5.2
2018	-19.3	-8.5	-6.2	-37.1
2019	-30.5	-16.6	-12.7	-36.5

Seasonal Average Variations (T-index) SC (24)				
Year	**Winter**	**Spring**	**Summer**	**Autumn**
2009	-4.0	0.0	-4.7	-2.7
2010	12.7	21.7	16.3	22.7
2011	25.7	55.7	47.0	84.0
2012	79.3	70.0	74.7	75.3
2013	67.0	81.7	79.7	76.7
2014	96.3	113.3	83.7	94.0
2015	98.7	91.0	66.0	45.3
2016	53.0	36.7	26.3	19.0
2017	14.3	7.0	1.7	11.3
2018	5.3	-1.7	-4.7	-10.3
2019	-5.7	-5.7	-13.3	-13.0

2.1. Correlation between IF2 and T-index

In this work, the cross-correlation of the seasonal variations for the studied indices was examined to demonstrate the inverse relationships between the two parameters, which enabled us to propose the mutual mathematical equations between the two studied indices and thus calculate both parameters' values in terms of the other when the second parameter's data is unavailable. The examination was conducted over two distinct time spans: from 1996 to 2008 and from 2008 to 2019. These intervals correspond to two solar cycles, Solar Cycle 23 and Solar Cycle 24. Figures (2) and (3) depict the correlated relationships between the seasonal average values of two examined index pairs: (IF2 Vs. T-index) and (T-index Vs. IF2) for Solar Cycles 23 and 24, respectively.

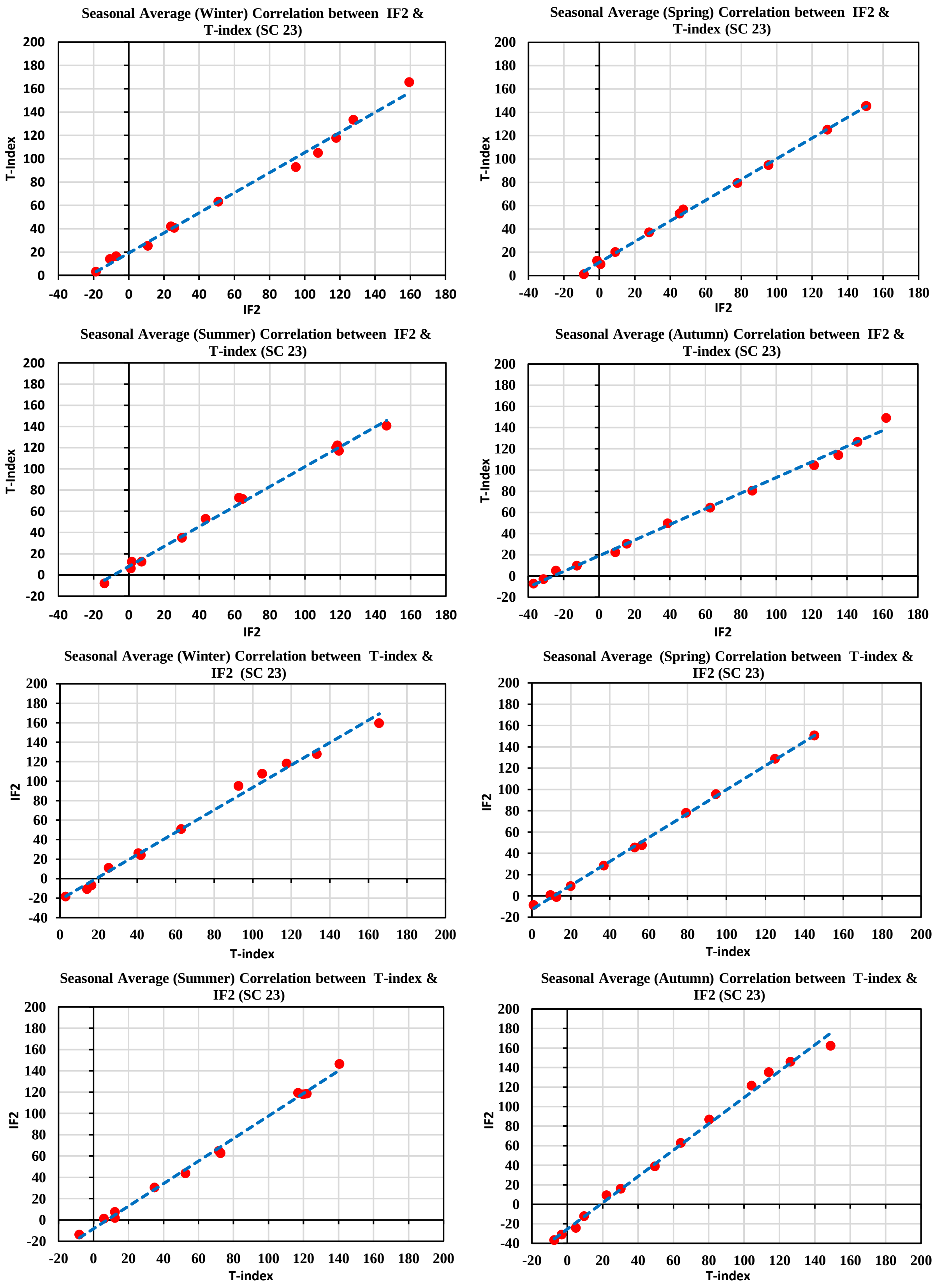


Figure 2: Seasonal cross-correlation between (IF2 Vs. T-index), (T-index Vs. IF2) indices during solar cycles 23

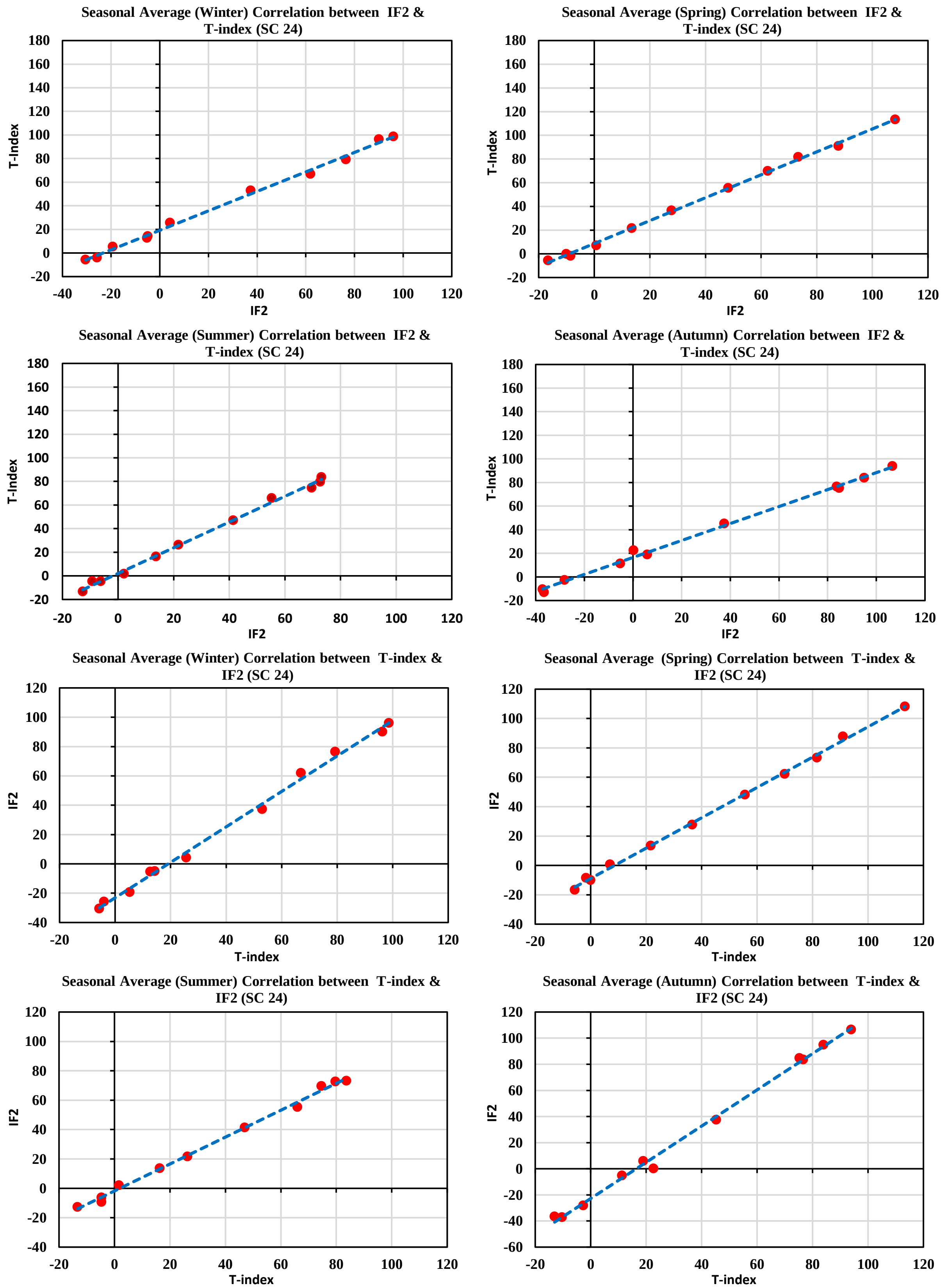


Figure 3: Seasonal cross-correlation between (IF2 Vs. T-index), (T-index Vs. IF2) indices during solar cycles 24

The examination results of the seasonal correlation between the tested indices (IF2 Vs. T-index) and (T-index Vs. IF2) for the investigated time spans from 1996 to 2008 and from 2008 to 2019 corresponding to the solar cycles 23 and 24, presented in Figures (2) and (3), demonstrate that the two indices are highly correlated to each other, as the determination coefficient (R^2) values were within the range (0.991 - 0.998) (0.996 - 0.998) during 23rd and 24th solar cycles, respectively. The calculated determination coefficient (R^2) values for each pairs of correlated indices are shown in Table (3).

Table 3: The calculated determination coefficients for the correlated index pairs during the seasonal time of solar cycles 23 and 24

Correlated Indices		**Seasons**	**Determination Coefficients (R^2)**	
			Solar cycle 23	**Solar cycle 24**
IF2	**T-index**	**Winter**	0.9914	0.9963
		Spring	0.9988	0.9984
		Summer	0.9956	0.9963
		Autumn	0.9945	0.9961

The findings of the analytic study indicated that the seasonal correlation relationship between IF2 and T-index could be effectively expressed by a *first order polynomial relationship*. As a result, the proposed correlative equation between the studied indices can be presented through the following equations:

$$\text{IF2 (T-index)} = \sum_{m=0}^{\infty} L_m \ (T\text{-}index)^m \qquad \text{………. (1)}$$

$$T\text{-}index\ \text{(IF2)} = \sum_{m=0}^{\infty} L_m \ (IF2)^m \qquad \text{………. (2)}$$

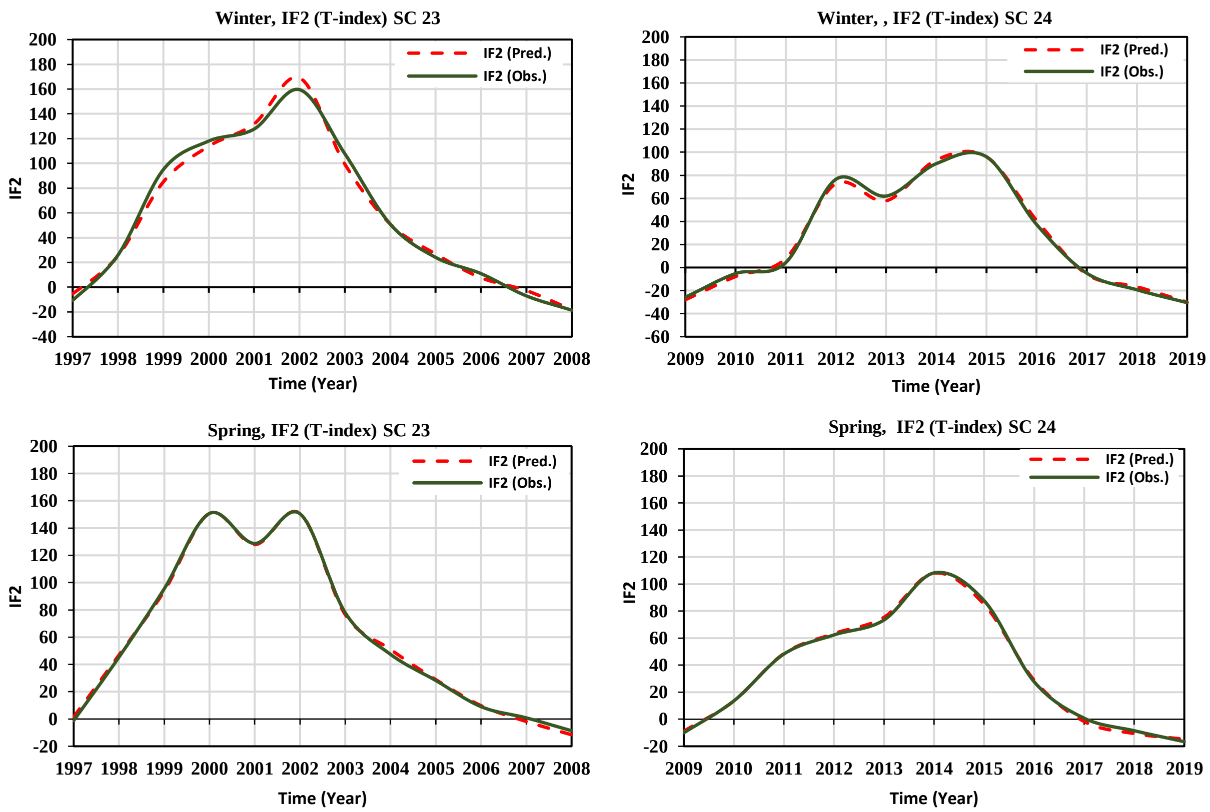
Where, (L_m) denotes the correlation coefficient for the (m^{th}) order (m = 0, 1, 2, ...) of the polynomial equation. The coefficients of correlation for the seasonal correlative relationship between the tested indices sets ((IF2 Vs. T-index), (T-index Vs. IF2)) were computed. Tables (4) present the determined values of the correlation coefficients between (IF2 & T-index) indices for the seasonal time of the solar cycles 23 and 24, respectively.

Table 4: Determined correlation coefficients values between (IF2 & T) indices for the seasonal times of the solar cycles 23 and 24.

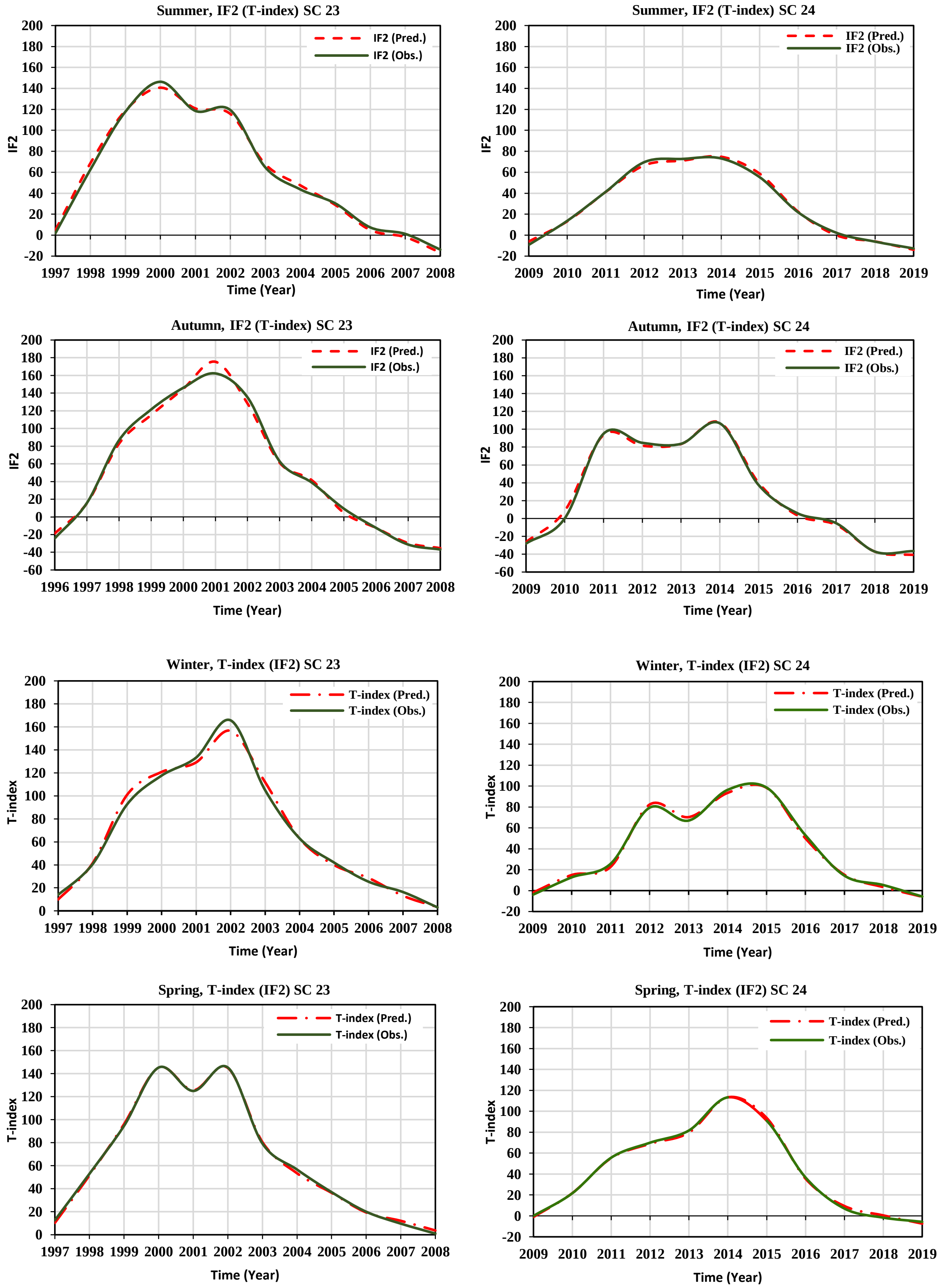
Solar Cycle 23				
Indices	Correlated Indices	Seasons	Correlation Coefficients	
			L_1	L_2
IF2	T-index	Winter	19.139	0.8615
		Spring	11.362	0.8881
		Summer	8.0283	0.9404
		Autumn	19.096	0.7377
T-index	IF2	Winter	-21.531	1.1507
		Spring	-12.707	1.1247
		Summer	-8.2448	1.0587
		Autumn	-25.456	1.3481

Solar Cycle 24				
Indices	Correlated Indices	Seasons	Correlation Coefficients	
			L_1	L_2
IF2	T-index	Winter	19.229	0.8243
		Spring	8.674	0.9672
		Summer	2.0394	1.0887
		Autumn	16.529	0.7185
T-index	IF2	Winter	-23.145	1.2086
		Spring	-8.8989	1.0323
		Summer	-1.7574	0.9151
		Autumn	-22.806	1.3863

To assess the precision of the proposed mathematical equations, a comparative investigation was conducted between the seasonal values predicted using the proposed correlation equations (Equations 1 and 2) with the observed seasonal data for the studied indices during the 23rd and 24th solar cycles. Figure (4) depicts the outcome of this comparison, showcasing the match between the seasonal predicted and observed values for both IF2 and T-index during solar cycles 23 and 24.



To be continued ...



To be continued ...

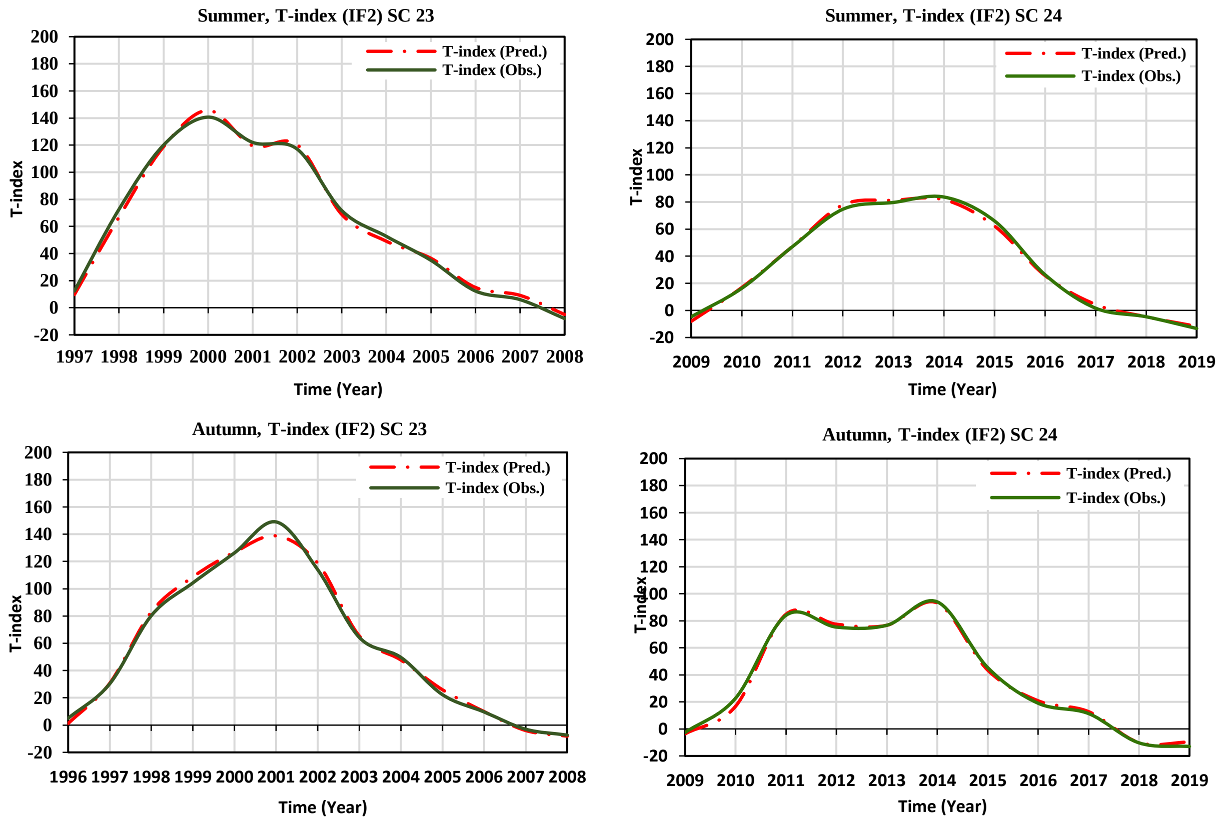


Figure 4: Comparison between the seasonal predicted and observed values of IF2 and T-index during solar cycles 23 and 24

2.2 Statistical Calculations

In this research, a statistical investigation of IF2 and T-index values was conducted through analyzing the dataset generated (predicted values) from the proposed correlation equations (Equations 1 and 2) for (IF2, T-index) and its comparison with the observed dataset across all seasons during the studied periods spanning through the two selected solar cycles. The statistical investigation of these datasets was performed using various statistical analysis methods, including the Normalized Root Mean Square Error (NRMSE), Correlation Coefficient (R), Determination Coefficient (R^2), Mean Difference (Mean Diff.), and Normalized Mean Absolute Error (NMAE). The outcomes of these statistical calculations for the seasonal predicted and observed values of the correlated indices during Solar Cycles 23 and 24 are presented in Table (5).

Table 5: Statistical calculation results of the seasonal predicted and observed values for correlative indices during solar cycles 23 and 24.

Solar Cycle 23				
IF2 VS. T-index				
Statistical Methods	Seasons			
	Winter	Spring	Summer	Autumn
Corr. Coeff. (R)	0.996	0.999	0.998	0.997
Det. Coeff. (R^2)	0.991	0.999	0.996	0.994
NRMSE	0.096	0.032	0.060	0.099
Mean Diff.	0.000	0.003	-0.002	0.001
NMAE	0.078	0.026	0.055	0.073

Solar Cycle 24				
IF2 VS. T-index				
Statistical Methods	Seasons			
	Winter	Spring	Summer	Autumn
Corr. Coeff. (R)	0.998	0.999	0.998	0.998
Det. Coeff. (R^2)	0.996	0.998	0.996	0.996
NRMSE	0.111	0.047	0.068	0.119
Mean Diff.	-0.002	0.001	0.000	-0.001
NMAE	0.097	0.039	0.056	0.087

3. Discussion

The analytical investigation that has been conducted, comparing the datasets produced using the proposed correlation equations with the observed dataset for the two examined ionospheric indices will be discussed. In Figure (1), the monthly patterns of the examined indices exhibited nearly identical variations during specific months of the year, corresponding to the seasonal periods across the studied years. However, a distinction was observed during the peak of solar cycle 23 (in 2001). During this period, the monthly behavior of the IF2-index diverged from its pattern during the peak of solar cycle 24 (in 2014). In solar cycle 23, the IF2-index demonstrated an increase during June followed by a decrease in July. Conversely, in solar Cycle 24, the opposite trend was evident, with a decrease in June followed by an increase in July. Additionally, the monthly behavior of the T-index displayed similar patterns with varying values during the peak solar cycle years 2001 and 2014. In 2001, the highest values were observed in December for IF2 and November for the T-index. Conversely, in 2014, both studied indices, IF2 and T-index, reached their highest values in March. During the minimum solar cycle years 1996 and 2009, the monthly behavior of the IF2-index exhibited more fluctuations compared to the T-index, which remained relatively stable across both solar cycles. The study findings regarding the seasonal correlation between the investigated indices (IF2 Vs. T-index) and (T-index Vs. IF2), depicted in Figures (2) and (3), demonstrate a highly correlation between the two indices. This conclusion is supported by the calculated determination coefficient (R^2) values, which are presented in Table (3). These values ranged from 0.991 to 0.998 for solar cycle 23 and from 0.996 to 0.998 for solar cycle 24. Furthermore, the mathematical correlation between the examined indices was identified as a first-order polynomial equation. Accordingly, proposed mathematical correlation formulas are presented in equations (1) and (2). These formulas exhibited a highly accurate fit between the observed values and the generated datasets across all seasons. The outcomes of the seasonal predicted values, which were calculated using the proposed mathematical equations and depicted in Figure (4), demonstrated that the patterns of the two examined indices, IF2 and T-index, closely matched the observed values for all seasons throughout solar cycles 23 and 24. Additionally, the results of the statistical parameter calculations, including NRMSE, R, R^2, Mean Diff., and NMAE, conducted between the predicted and observed values of the two selected indices across the study years, as displayed in Table (5), gave very good outcomes. These results indicated that the smallest values for NRMSE and NMAE were achieved during both Solar Cycles 23 and 24, specifically in the spring season, with values of 0.032 and 0.047 for NRMSE and 0.026 and 0.039 for NMAE, respectively. Moreover, the statistical parameter Mean Diff. demonstrated its best value during the winter season in Solar Cycle 23 and during the summer season in Solar Cycle 24.

4. Conclusions

Based on the results derived from the comparative analysis of the seasonal variations in the IF2 and T ionospheric indices during Solar Cycles 23 and 24, as well as the preceding discussion, the following summarizes the conclusions.

1. The monthly behavior of the examined indices exhibited nearly identical variations during specific months of the year, representing the seasonal patterns across the studied years.
2. The findings of the seasonal correlation between the investigated indices (IF2 Vs. T-index) revealed a high correlation between the two indices.
3. The mathematical correlation between the examined indices was identified as a first-order polynomial equation.
4. The proposed Mathematical correlative formulas exhibited a highly accurate fit between the observed values and the generated datasets across all seasons.
5. The outcomes of the seasonal predicted values, calculated using the proposed formulas demonstrated that the patterns of the two examined indices, closely matched the observed values for all seasons throughout solar cycles 23 and 24.
6. The results of the statistical parameter calculations conducted between the predicted and observed values of the two selected indices across the study years gave very good outcomes.

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