National and Kapodistrian University of Athens
Faculty of Physics

Geomagnetic storms of the solar cycle 24

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Abstract: Solar cycle 24 has been characterized by a low solar activity and it is the smallest sunspot cycle in over a century. Despite of this fact a number of geomagnetic storms from G1 to G4 scale, according to National Oceanic and Atmospheric Administration (NOAA) classification, was noticed. In this work the characteristics of these geomagnetic storms like the scale level, the origin of the storm (CME or CIR) and the duration during the period 2009 to 2016 have been studied. It is noteworthy that the year 2015 was characterized by long geomagnetic quiet periods with a lot of geomagnetically active breaks, although it is on the declining phase of the current solar cycle. A comparison with the geoeffectiveness of the previous cycle 23 was also carried out. Furthermore, a statistical analysis of these events and a comparative study of the forecasting and the actual geomagnetic conditions are performed using data from the NOAA space weather forecasting center and from the Athens Space Weather Forecasting Center (ASWFC) as well. These forecasting centers estimate and provide every day the geomagnetic conditions for the upcoming days giving the values of the geomagnetic index Ap.

Introduction

A geomagnetic storm is an intense and prolonged magnetic activity due to the strong coupling of Earth's magnetosphere with solar wind. The increase in the solar wind flux caused by solar phenomena, such as a high-speed stream of solar wind from a coronal hole which refers as a corotating interaction region (CIR), an Interplanetary Coronal Mass Ejection (ICME), or a combination of these events (Zhang *et al.*, 2007). The extra pressure on the magnetosphere and this interaction with the magnetosphere gives as a result a transfer of an increased amount of energy into the magnetosphere.
The geomagnetic storm have different scales due to the possible effects on people and systems. These scales introduced by the NOAA (http://www.swpc.noaa.gov/noaa-scales-explanation) and based on the values of Kp index are presenting on Table 1.

Geomagnetic Storms

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	Extreme	**Power systems:** Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** Pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).	Kp = 9	4 per cycle (4 days per cycle)
G 4	Severe	**Power systems:** Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** May experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** Induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	**Power systems:** Voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** Intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).	Kp = 7	200 per cycle (130 days per cycle)
G 2	Moderate	**Power systems:** High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).	Kp = 6	600 per cycle (360 days per cycle)
G 1	Minor	**Power systems:** Weak power grid fluctuations can occur. **Spacecraft operations:** Minor impact on satellite operations possible. **Other systems:** Migratory animals are affected at this and higher levels;	Kp = 5	1700 per cycle (900 days per cycle)

Table 1. *Classification of geomagnetic storms from NOAA with Kp index*

Storms	Class	Kp index	Ap index
G5	Extreme	K_p=9	400
G4	Severe	K_p=8	179-300
G3	Strong	K_p=7	111-154
G2	Moderate	K_p=6	67-90
G1	Minor	K_p=5	39-56

Table 2. *Classification of geomagnetic storms from NOAA with Kp and Ap indices*

Identification-data analysis

The determination of these geomagnetic storms is based on the measurements of Kp index and especially when Kp ≥ 5 the event is characterized as a storm. The storm scales are defined in Table 1. The preliminary list of geomagnetic storms of 24th solar cycle is presented in Table 2.
The storm is the result of Earth's magnetosphere with an ICME, a CIR or a combination of these events. If Kp index value has two maximum values in a period of two-three days a further investigation was applied in order to determine the origin of the storm. If the source is different (high speed stream and ICME) then we count this event as two different storms. The result of this analysis is a reference catalogue of 245 well defined geomagnetic storms during the time period 2009-2016 covering the 24 solar cycle.
A comparison of the occurring storms per year between 23rd and 24th solar cycles is presented in Figures 1 and 2.

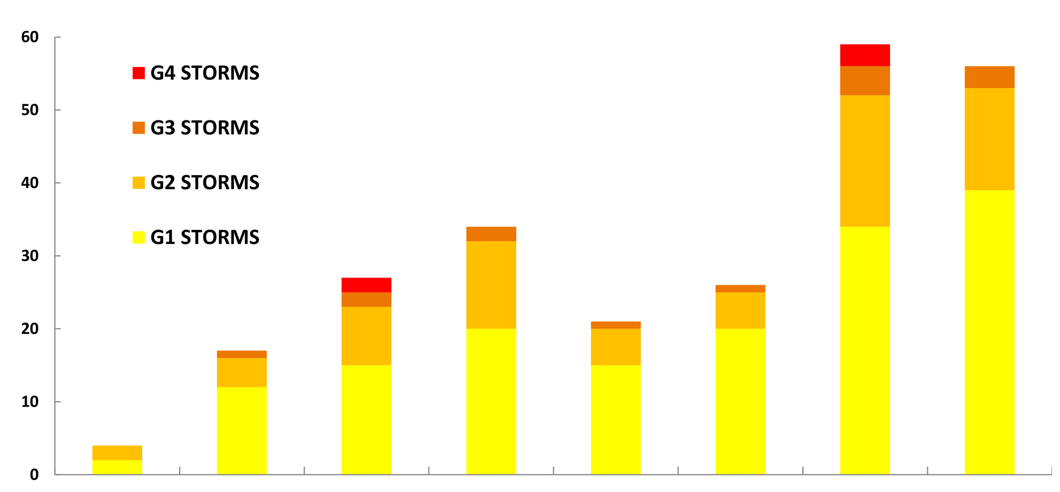


Figure 1. *Storms per year and per class scale of 24th solar cycle. It is clear that G4 storms were very rare during these years. This is in accordance with the fact that 24th solar cycle is the weakest solar cycle in over a century*

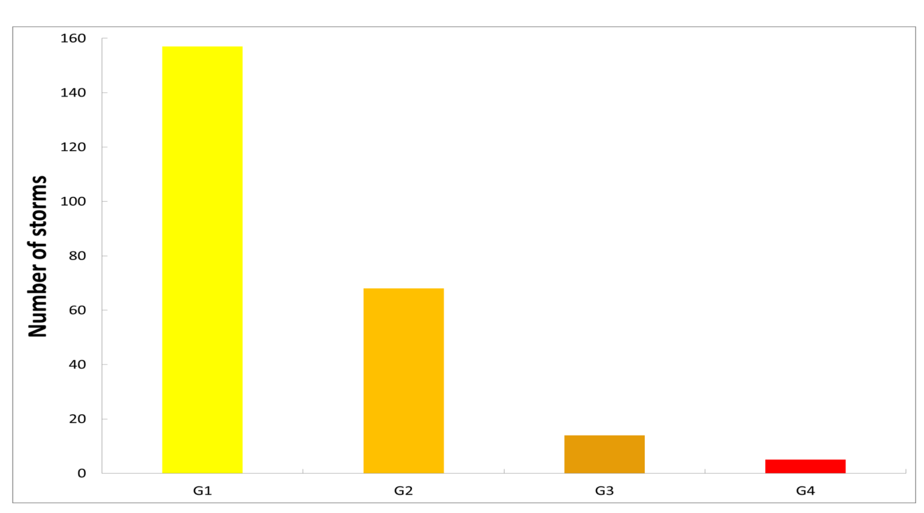


Figure 2. *Distribution of Storms according to their class for 24th solar cycle.*

Year	Number of storms G1	G2	G3	G4
2009	2	2	0	0
2010	12	4	1	0
2011	15	8	2	2
2012	20	12	2	0
2013	15	5	1	0
2014	20	5	1	0
2015	34	18	4	3
2016	39	14	3	0
TOTAL	157	68	14	5

Table 3. *List of geomagnetic storms of 24th solar cycle*

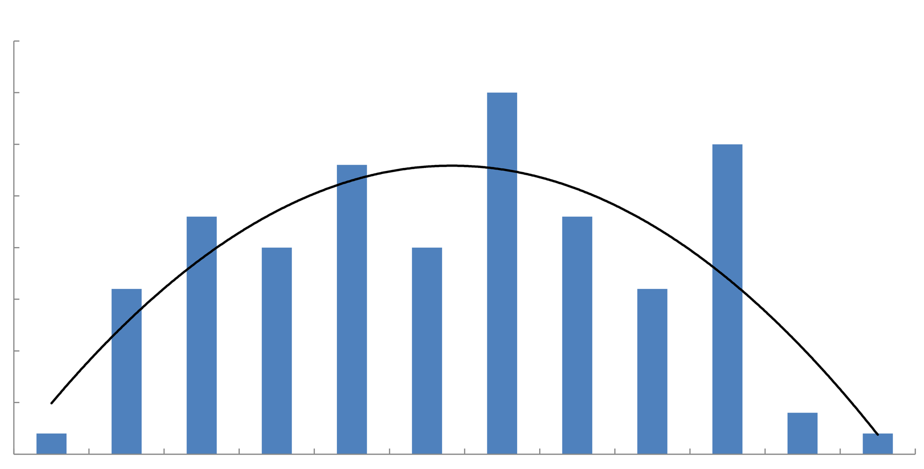
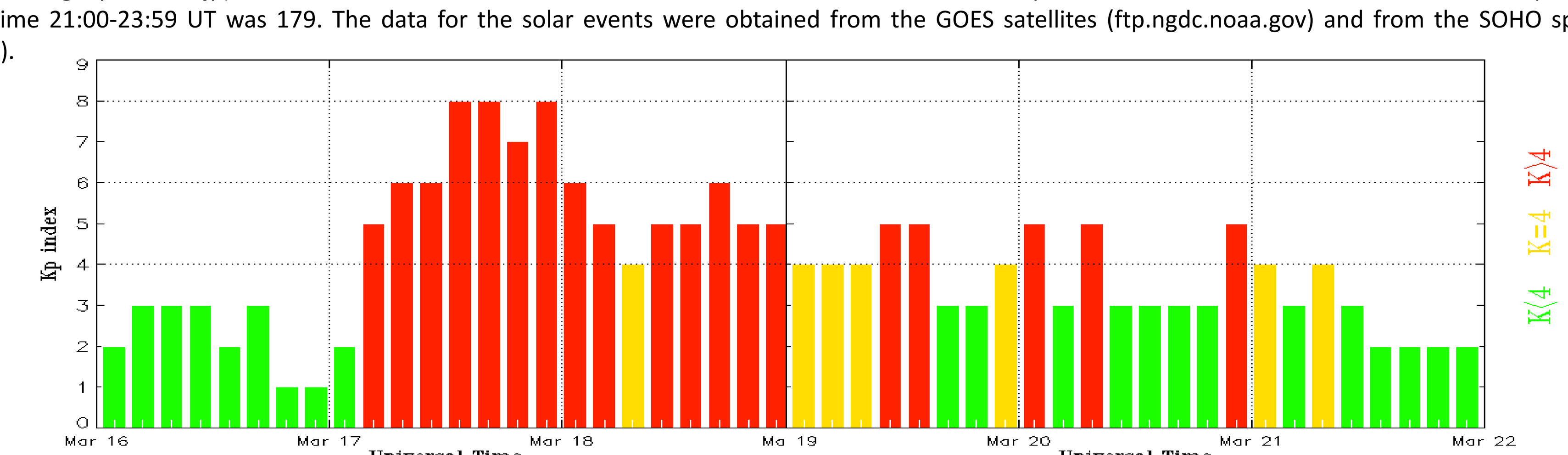


Figure 3. *Storms per year of the 23rd cycle (Balveer S. Rathore et al., 2012). It is also clear that the maximum of the occurring storms is not in accordance with the maximum of the 23rd cycle (at 2000).*

The G4 geomagnetic storm of March 2015

A solar flare with importance X2.1 on 11/03/2015 at 16:22 UT from the AR 2297, S17E22, which area gave some days after a CME which is responsible for the G4 geomagnetic storm of 17 March 2015 (Mavromichalaki *et al.*, 2015). This geomagnetic storm was the result of the interaction between the complex solar activity which spotted at the active region AR2297 (S22W29) and Earth's magnetosphere. Especially a magnetic filament erupted between 00:45 UT and 02:00 UT with also a C9.1 class solar flare with peak time at 02:13 UT. This combination of blasts hurled an Earth directed CME into the interplanetary space. This ICME arrived in the first hours of March 17th and a minimum of Dst index of -223 nT (preliminary data, wdc.kugi.kyoto-u.ac.jp) was noticed at 22:00-23:00 UT. Some hours before at 12:00-15:00 UT the Kp index reached the maximum value of 8 and Ap index maximum value was for the time 21:00-23:59 UT was 179. The data for the solar events were obtained from the GOES satellites (ftp.ngdc.noaa.gov) and from the SOHO space telescope (cdaw.gsfc.nasa.gov).



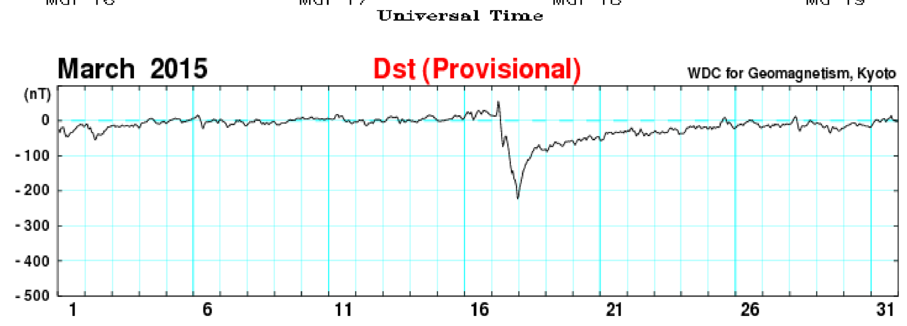


Figure 4. *The Kp values from March 16 up to March 21 2015 with the maximum ones noticed on March 17 (Top panel). The corresponding Dst index values with the minimum one during the G4 storm on March 17 (Left panel).*

Forecasting of Geo-Storms

Website of A.Ne.Mo.S. : http://cosray.phys.uoa.gr

http://cosray.phys.uoa.gr/index.php/space-weather-report

The continuous space measurements by ACE, SOHO, GOES, SDO, PROBA, STEREO A and B, together with ground based observatories as neutron monitors and magnetometers has led to the implementation of Space Weather Centers for the short and long term forecasting of the planetary geomagnetic index Ap. The **Athens Space Weather Forecasting Center (ASWFC)** provides a daily report that includes current geomagnetic conditions in near-Earth space (McPherron , 1999; Abunina *et al.*, 2012,) as well as a 3-day forecast of the planetary geomagnetic index Ap. This Estimation of the Ap index is based on a set of rules that includes a number of known parameters/properties of Ap index (Gerontidou *et al.*, 2013).

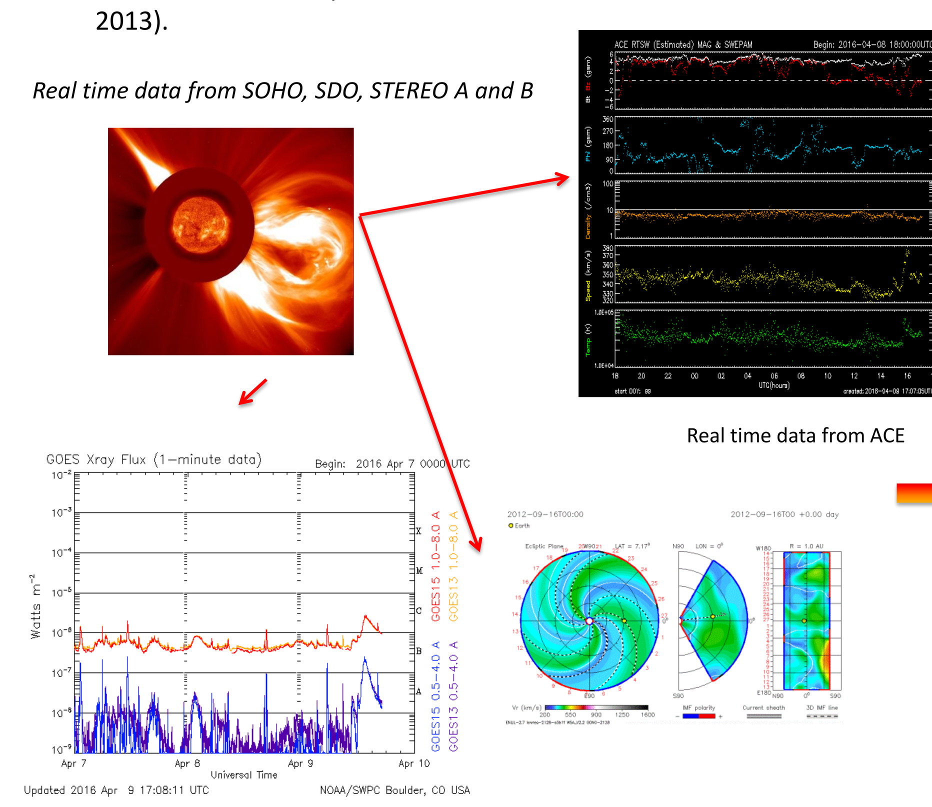


Figure 5. *The combination of all available information in order to produce the daily forecast of space weather by ASWFC.*

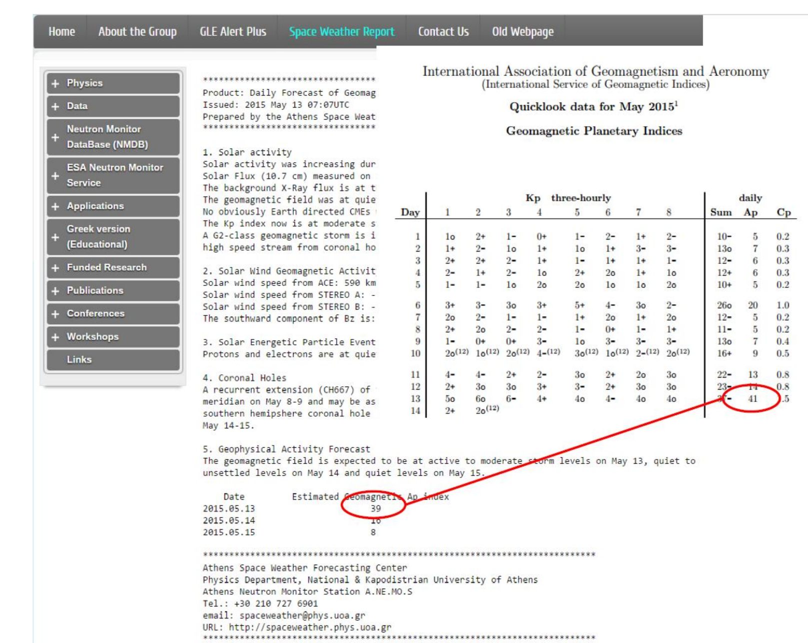
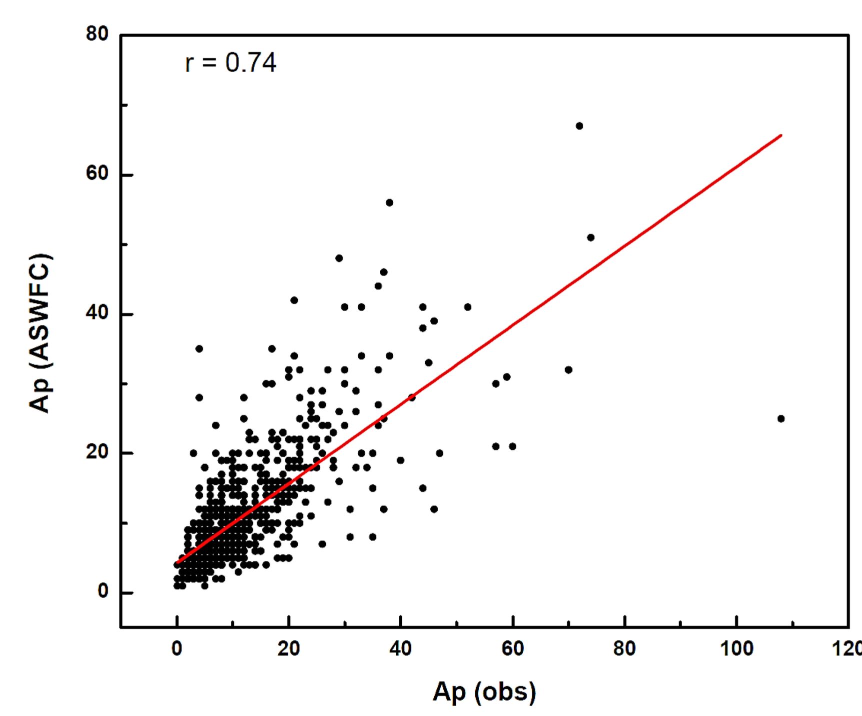
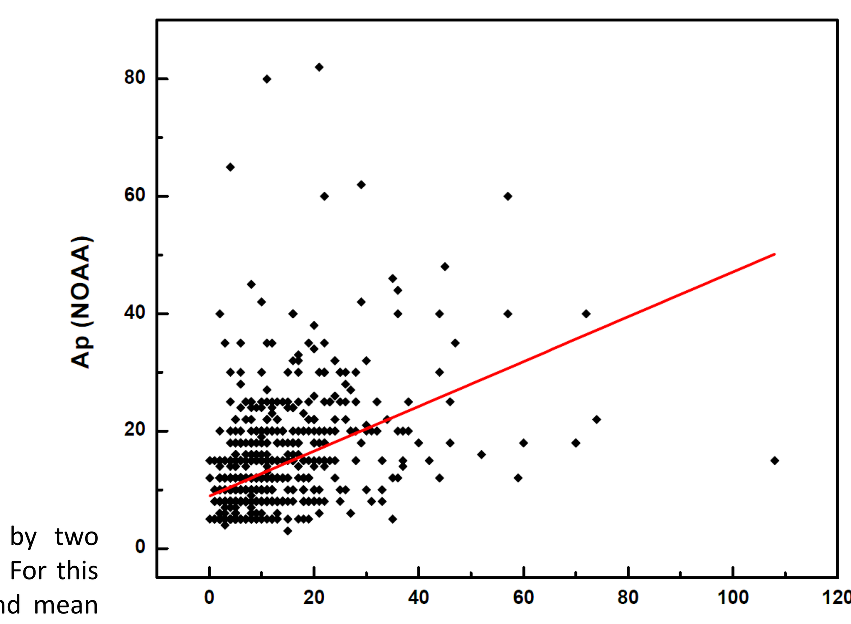


Figure 6. *The website of ASWFC with the corresponding daily forecast. The estimated Ap index (39) and the observed value (41) by IAGA are presenting as an example of a successful forecast of a G2 geomagnetic storm of May 13th 2015.*



	ASWFC
RMSD*	6.964
MAPE*	52.1%
Pearson r	0.736

	NOAA
RMSD*	10.400
MAPE*	128.2%
Pearson r	0.440



A comparison between the estimated values of Ap geomagnetic index by two forecasting centers ASWFC and NOAA is presented, for the years 2014-2016. For this purpose statistical functions as the root mean square deviation –RMSD– and mean absolute percentage error –MAPE– were calculated between the observed and the estimated values of Ap index for both centers. A linear fit was applied also between the observed and estimated values for ASWFC and NOAA and the cross correlation coefficient has been calculated. The results are being presented in the previous tables.

Conclusions

- **During the years 2009-2016 a number of 244 geomagnetic storms were occurred, namely 157 G1, 68 G2, 14 G3 and 5 G4 ones.**
- **Most of the defined G1 and G2 storms are due to the corotating interaction regions (CIRs), while the G3 and G4 ones are mostly due to ICMEs or to a combination of CIRs and ICMEs.**
- **High number of geomagnetic storms occurred in 2015 and 2016, although the 24th solar cycle was the weakest cycle over a century.**
- **No clear correlation between the number of storms and the intense of a solar cycle (number of sunspots) was noticed for the 23rd and the 24th solar cycle. There is a shift of the maximum of storms for about 2 years from the maximum of the cycles. Further investigation is necessary for the explanation of this shift.**
- **The statistical analysis of the observed daily Ap values and those estimated by the two forecasting centres ASWFC and NOAA for the examined geomagnetic storms revealed that ASWFC had a RMSD equal 18.03 and a MAPE of 32.8% while NOAA had 22.86 and 42.4 respectively.**
- **The linear fit between the observed and estimated daily Ap values gave a cross correlation coefficient for ASWFC of r = +0.736 while for NOAA was r = +0.440**

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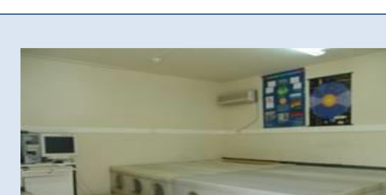

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