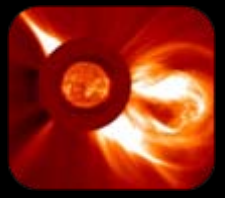
NATIONAL AND KAPODISTRIAN UNIVERSITY OF ATHENS
FACULTY OF PHYSICS
Athens Space Weather Forecasting Center



Using the CME-index for short-term estimation of Ap geomagnetic index

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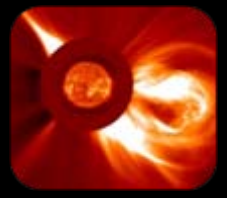
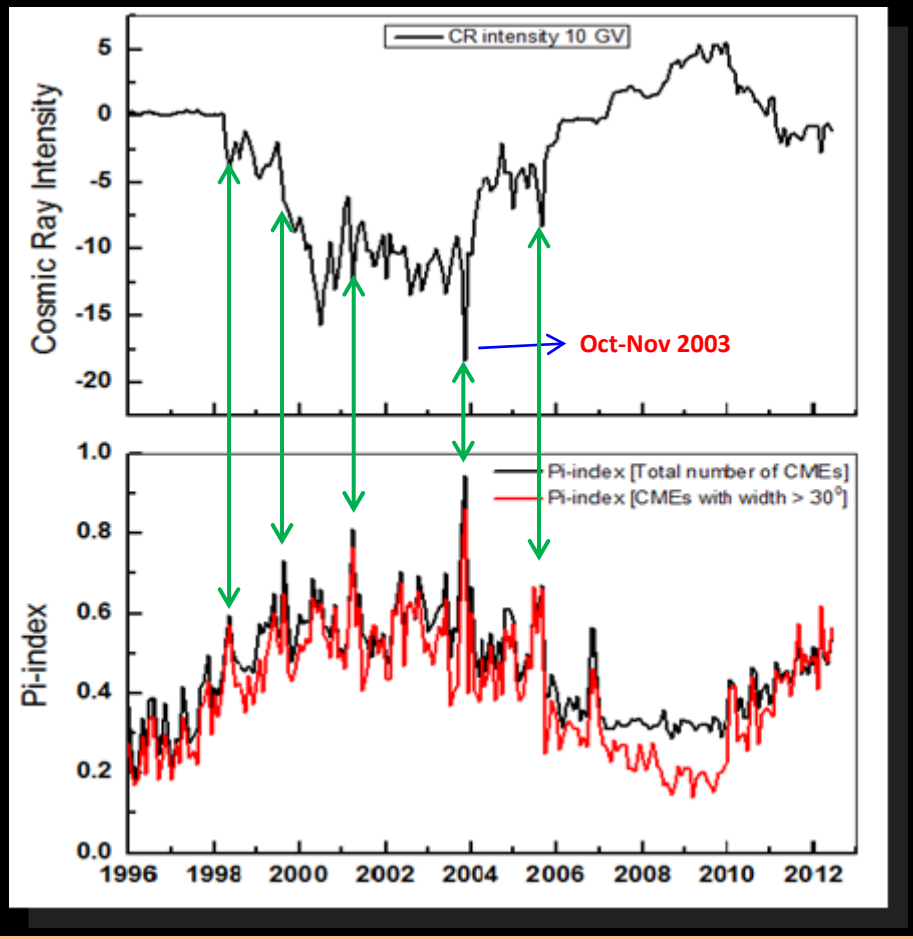


Overview

1. Anti-correlation between CMEs and Cosmic-Ray Intensity
2. The CME-index in the Long-term Modulation of the Cosmic-Ray intensity
3. Connection of the CME-index and the geomagnetic index Ap
4. Transform of the CME-index from a monthly to a daily variable
5. A new relation for Ap index and CME-index – Application to Space Weather conditions
6. Athens Space Weather Forecasting Center

CME-index and Cosmic-Rays



Anti-correlation between CMEs and Cosmic-Ray intensity

r = -0.84 with 0 months time-lag

This index follows the relation:

$$P_i = \alpha \cdot \frac{Nc}{Nc_{max}} + \beta \cdot \frac{Vp}{Vp_{max}}$$

$$\alpha + \beta = 1$$

$$\alpha, \beta > 0$$

Nc: The monthly number of CMEs,
Nc_{max}: The maximum Nc for the examined period
Vp: The average linear speed of the CMEs per month,
Vp_{max}: The maximum Vp for the examined period

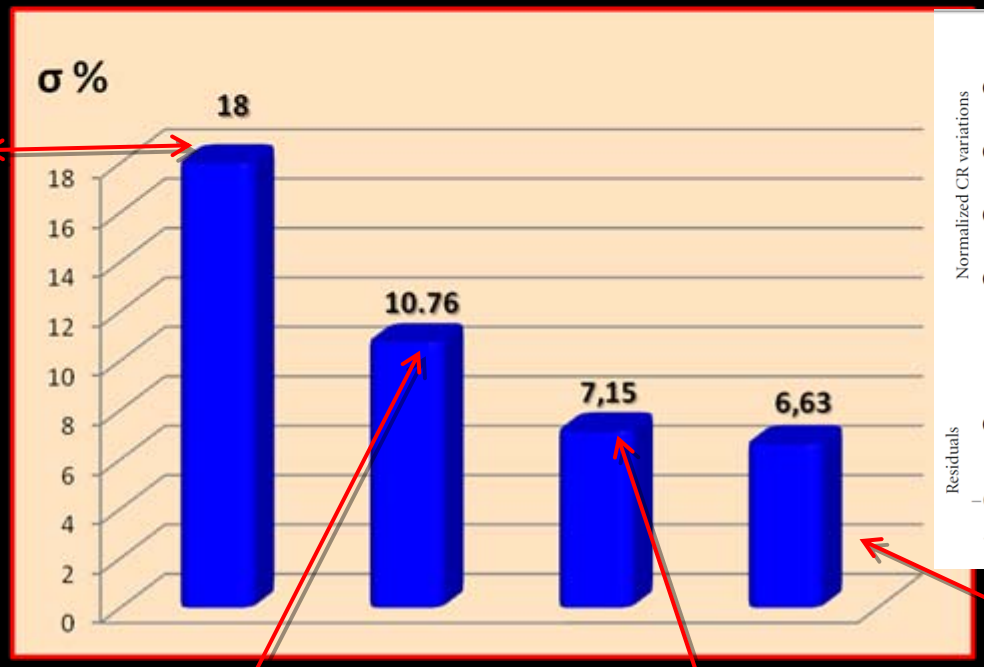
Paouris, 2013
Mavromichalaki and Paouris, 2012

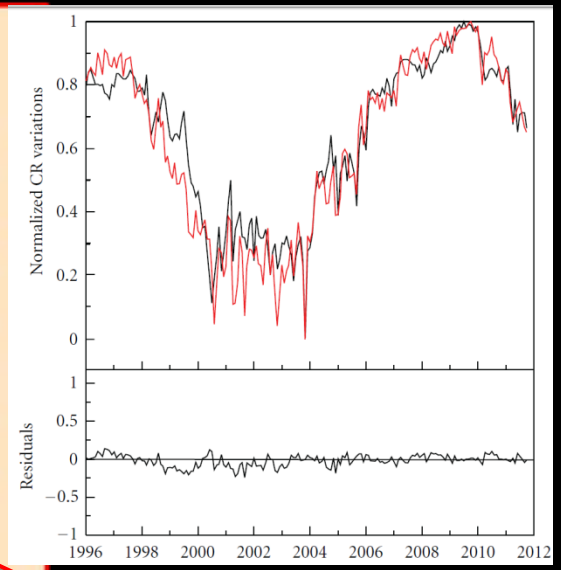
CME-index and Long-term Modulation

$$I = f\left(Rz, Nf, Ap\right)$$

Xanthakis *et al., 1981*
Mavromichalaki *et al. 2005*

• A proxy which applied with success in Long-term Modulation of Galactic Cosmic-Rays





$$I = f\left(Rz, Nc, Ap, HCS\right)$$

Mavromichalaki, Paouris and Karalidi, 2007

$$I = f\left(Rz, P_i, IMF, HCS\right)$$

Paouris et al., 2012

$$I = f\left(Rz, P_i^*, IMF, HCS\right)$$

Mavromichalaki and Paouris, 2013

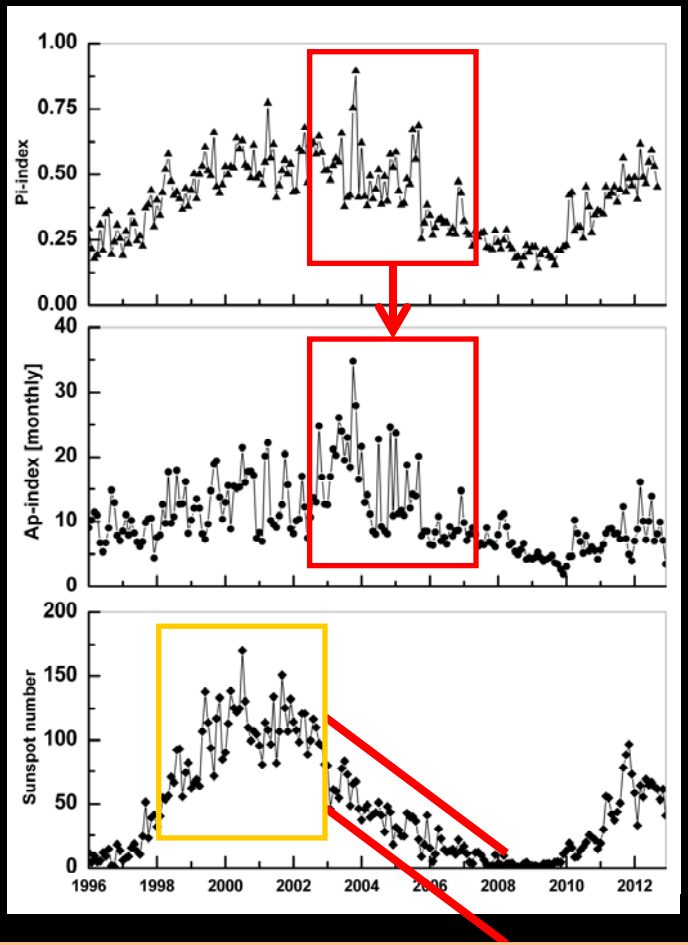
CME-index and Ap index

Correlation Analysis:

Ap-index - Rz	
Pearson cc	**0.47**
Spearman cc	0.57

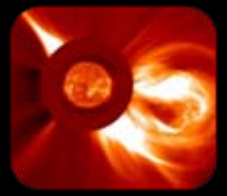
Ap-index - P_i-index	
Pearson cc	**0.68**
Spearman cc	0.67

P_i-index - Rz	
Pearson cc	0.76
Spearman cc	0.85



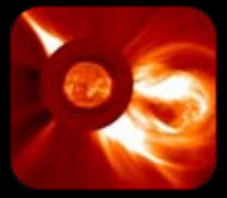
Sunspot number:
No information for extreme events!

CME-index:
Based on the extreme events!
"This index is strongly connected to extreme events and not only to the overall solar activity as the sunspot number does" (*Paouris, 2013*)



CME-index short-term

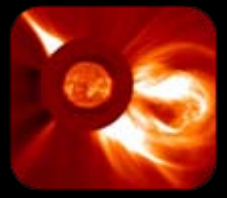
Long-term	Short-term
Monthly values	Daily values
Nc: Number of CMEs per month Nc_{max}: The max value of Nc for the examined period.	**Width**: The angular width of CME as a factor for the possible consequences of the magnetic cloud in the interplanetary space $Width_{max}$: 360° for HALO CMEs
Vp: Average of linear speed Vp_{max}: The max value of Vp for the examined period.	**Vp**: The linear speed of the CME Vp_{max}: The max value of Vp for the examined period.
Events per month → Pi-index value	**Each event → Pi-index value**



Data Collection

- Geomagnetic storms Ap > 100
- Examined period (1996 – 2012) number of events = 20

Dataset:
1.Ap geomagnetic index,
2.CMEs and their characteristics (linear speed, width)
3.CME-Flare connection
4.Data for possible shock (time, start, end)

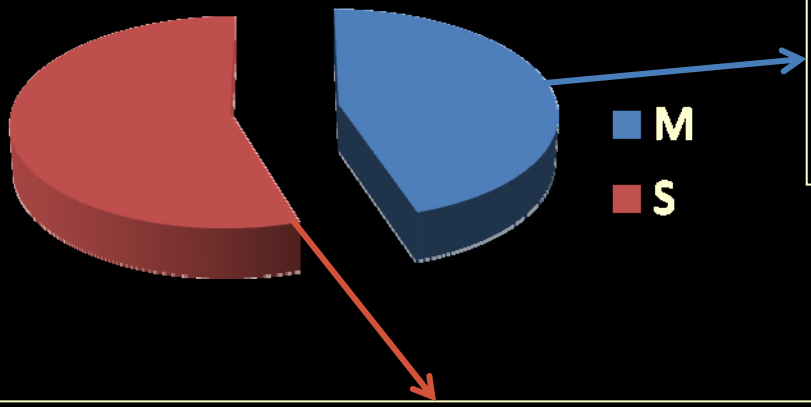


Data Collection

	Dst		Ap		Driver	CME			Flare Class	Source	IP solar wind structure type	Shock	ICME	
	Date / Time U.T.	Int. (nT)	Date / Time U.T.	Int (max)		Time U.T.	Linear Speed Km/s	Width				Time U.T.	Start	End
1	1998/05/04 06:00	-205	1998/05/04 03:00-06:00	300	M	05/02 14:06	938	HALO	X1.1	AR8210	PICME-SH	05/04 02:15	--	--
					--	05/02 05:31	542	HALO	C5.4	AR8210	--	--	--	--
					--	05/01 23:40	585	HALO	M1.2	AR8210	--	--	--	--
					--	04/29 16:59	1374	HALO	M6.8	AR8210	--	05/01 21:21	05/02 05:00	05/04 02:00
2	1998/08/27 10:00	-155	1998/08/27 00:00-06:00	207	S	08/24 21:50	--	--	X1.0	AR8307	SH+ ICME	08/26 06:40	08/26 22:00	08/28 00:00
3	1998/09/25 10:00	-207	1998/09/25 06:00-09:00	236	S	09/23 06:40	--	--	M7.1	AR8340	SH+ MC	09/24 23:20	09/25 02:00	09/26 16:00
4	2000/07/16 01:00	-301	2000/07/15 18:00-21:00	400	S	07/14 10:54	1674	HALO	X5.7	AR9077	SH+ MC	07/15 14:15	07/15 19:00	07/17 08:00
5	2000/08/12 10:00	-235	2000/08/12 06:00-12:00	179	S	08/09 16:30	702	HALO	C2.3	AR9114	SH+ MC	08/11 18:49	08/12 05:00	08/13 22:00
6	2000/10/05 14:00	-182	2000/10/05 06:00-09:00 12:00-15:00	179	M	09/29 21:50	173	274	NO	UNK	MC+PMC-SH+ ICME	10/03 01:02	10/03 10:00	10/05 06:00
					--	10/01 17:50	586	136	C5.0	QS	--	10/05 03:28	10/03 13:00	10/05 06:00
7	2001/03/31 09:00	-387	2001/03/31 03:00-09:00	300	M	03/29 10:26	942	HALO	X1.7	AR9393	SH(M)+ICME(M)	03/31 01:14	03/31 05:00	04/03 15:00
					--	03/28 12:50	519	HALO	M4.3	AR9393	--	--	--	--

(Zhang *et al.*, 2007)

Analysis of events



S – Events: **45%**
The storm is associated with a single ICME and a single CME at the Sun

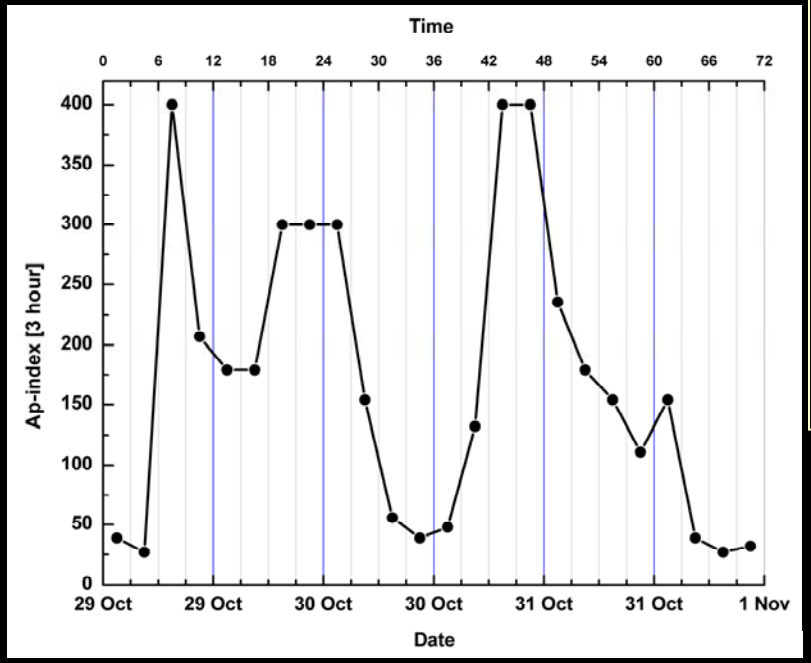
M – Events: **55%**
The storm is associated with a complex solar wind flow produced by multiple interacting ICMEs arising from multiple HALO CMEs launched from the Sun in a short period

Events and Flare connection	M Events	S Events	%
NO flare	1	1	10
C	0	2	10
M	3	3	**30**
X	5	5	**50**

80%

A case study – Oct 30-31, 2003

Example of geomagnetic storm of 2003/10/30:



1. ID of the event:
Ap (daily) = **191.13**,
2. CME which caused the storm:
Date/Time = 29/10/2003, 20:54 U.T.
Linear velocity = **2029** km/s
Width = 360 (HALO)
associate with solar flare: **X10.0**
AR : 0486
3. Arrival Date/Time for the shock: 30/10/2003
At 16:19 U.T.

(2. and 3. from Zhang *et al.*, 2007)

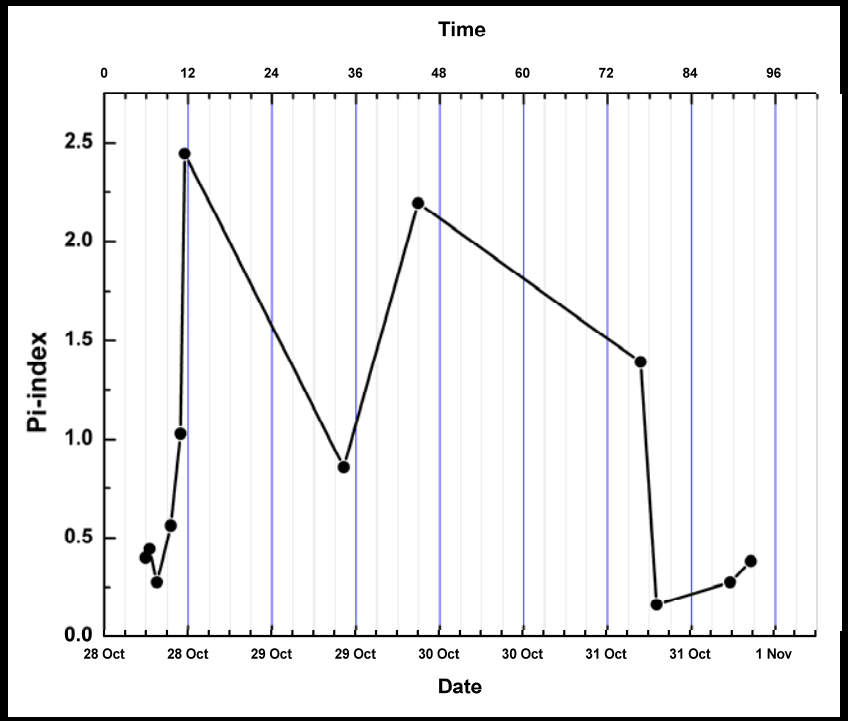
A case study – Oct 30-31, 2003

CME-index in daily resolution, based on the Equation:

$$P_i = \frac{Vp}{Vp_{\max}} + \frac{w}{w_{\max}}$$

Vp_{max} = The maximum velocity from the examined events,
Considering also the storm level,
Vp_{max} = 1700 km/s
w_{max} = 360°, for HALO CMEs

We calculate P-index values from 28/10/2003 up to 31/10/2003:



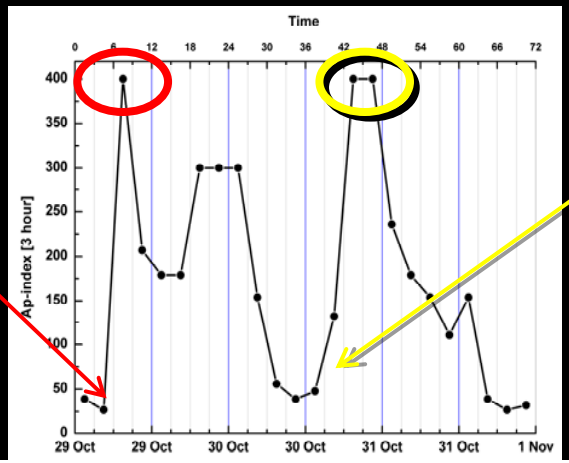
A case study – Oct 30-31, 2003

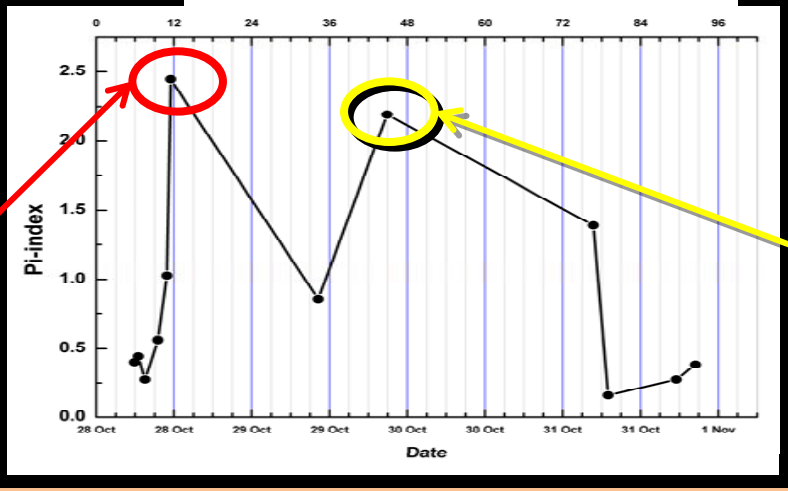
Arrival Time for Shock: 05:58 U.T.

For Δt = 18h 30min
S = 1 A.U., **calculated**
V = **2250** km/s

$\Delta V/V_{obs}$ = 8.5 %

CME at
28/10/2003
11:30 U.T.
Observed
V = **2459** km/s



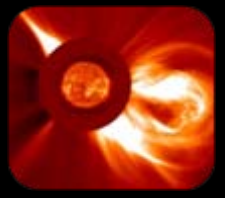


Arrival Time for Shock: 16:19 U.T.

For Δt = 19h 25min
S = 1 A.U., **calculated**
V = **2080** km/s

$\Delta V/V_{obs}$ = 2.5 %

CME at
29/10/2003
20:54 U.T.
Observed
2029 km/s



Ap-index from P_i-index

Determination of the best model function:

$$Ap = Ap_o + A \cdot e^{R_o \cdot P_i}$$

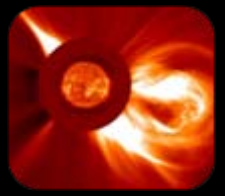
Ap_o = -226.5

A = 211.9

R_o = 0.43638

Ap calculated values

Pi: CME-index values



Results

Event	Ap_{calc}	Ap_{obs}	%
2003/05/29 18:00-24:00	239	236	1
2001/11/06 00:00-06:00	295	300	2
2003/10/30 18:00-24:00	390	400	3
2004/11/10 06:00-09:00	288	300	4
2001/11/24 06:00-09:00	248	236	5
2000/08/12 06:00-12:00	166	179	7
2003/10/31 00:00-03:00	325	300	8
2003/11/20 15:00-21:00	275	300	8
2003/08/18 15:00-18:00	135	154	13

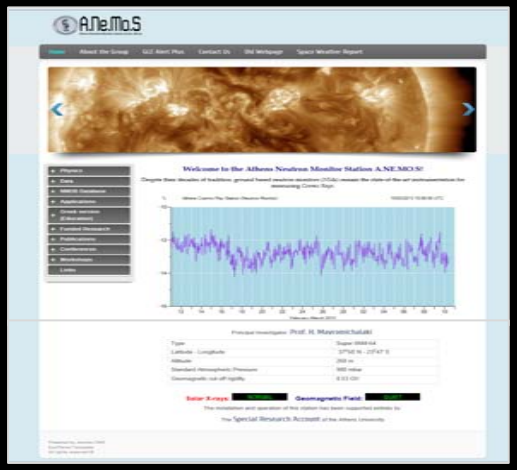
Divergence $(Ap_{calc} - Ap_{obs})/Ap_{obs}$ (%)	
< 10 %	8
< 20 %	1
< 30 %	2
< 40 %	3
> 40 %	4

Event	Ap_{calc}	Ap_{obs}	%
2004/07/27 12:00-15:00	235	300	22
2005/08/24 09:00-12:00	219	300	27
2000/07/15 18:00-21:00	277	400	31
1998/05/04 03:00-06:00	191	300	36
2001/03/31 03:00-09:00	191	300	36
2004/11/08 00:00-06:00	170	300	43
2000/10/05 06:00-09:00 12:00-15:00	82	179	54
2004/07/25 15:00-18:00	87	207	58
2005/09/11 06:00-09:00	359	179	100

A.Ne.Mo.S Applications

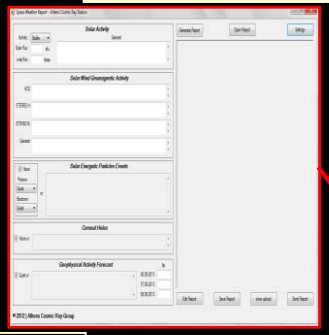
- **Athens Space Weather Forecasting Center**
- **Barometric coef.**
- **GLE Alert Plus – ESA SSA Project**

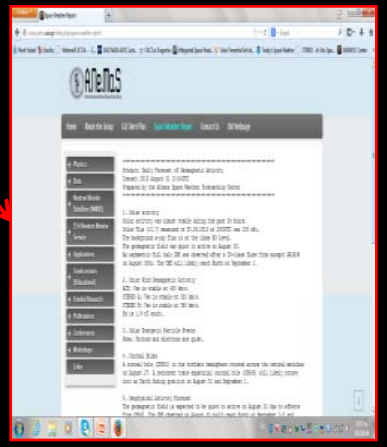
(http://cosray.phys.uoa.gr)



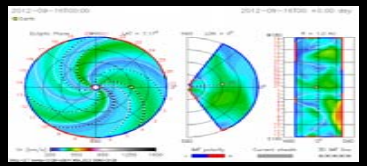
Estimation of the Ap index with a set of rules that include a number of known parameters/properties of Ap index, as well as current observations of the Sun and near-Earth space

Athens Daily forecast Report



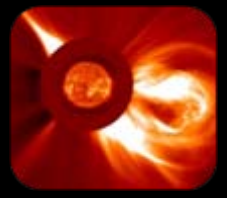


Real time MPEG movies from SOHO SDO PROBA STEREO A and B via **Media Download developed by Athens Cosmic ray group**



WSA –ENLIL CONE model-CME evolution

Autoregressive model (AR model)
a) Solar events, CMEs and Coronal holes
b) Magnetic activity 27-days before
c) Phase of solar cycle

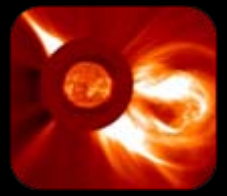


Conclusions

1. Cosmic-ray intensity and Pi-index are peak to peak correlated, (r=-0.84)
2. Ap index and P-index presents a higher correlation coefficient than in other indices
3. The most of the examined events with Ap>100, (9 S-Events, 11 M-Events) were associated with strong M- and X-flares
4. The estimated value of CME velocity was deviated from the observed one only 2.5% for the event of October 2003 (Halloween event)
5. The Ap values defined through the Pi-index values are based on an exponential model with a very good approximation.

In future work:

- This method will be useful for Space Weather studies and it will be applied to the Athens Space Weather Forecasting Center very soon
- This preliminary study will be extended to the events with Ap<100



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Institute of Ionosphere, Almaty, Kazakhstan
Institute for Space Research & Technology, Bulgarian Academy of Sciences, Sofia, Bulgaria

Thank You !

Athens NM Station