Article

Correlation between intense Solar Energetic Particle fluxes and atmospheric weather extremes

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Abstract: In the past two decades the world experienced an exceptional number of unprecedented extreme weather events, some causing major human suffering and economic damage, such as the March 2012 heat event, which was called "Meteorological March Madness." From the beginning of space era a correlation of solar flares with pressure changes in atmosphere within 2-3 days or even less was reported. In this study we wanted to test the possible relation of highly warm weather events in North-East America with Solar Energetic Particle (SEP) events. For this reason we compared ground temperatures T_M in Madison, Wisconsin, with energetic particle fluxes P measured by the EPAM instrument onboard the ACE spacecraft. In particular, we elaborated case events and the results of a statistical study of the SEP events related with the largest ($Dst \leq -150nT$) Coronal Mass Ejection (CME)- induced geomagnetic storms, between with the years 1997 – 2015. The most striking result of our statistical analysis is a very significant positive correlation between the highest temperature increase. ΔT_M and the time duration of the temperature increase ΔT_M ($r = 0.8$, $p < 0.001$) at "winter times" ($r = 0.5$, p , 0.01 for the whole sample of 26 SEP examined events). The time response of T_M to P was found to be in general short (a few days), but in the case of March 2015, during a gradual P8 increase, a cross-correlation test indicated highest c.c. within 1 day ($p < 0.05$). The March 2012 "meteorological anomaly" was elaborated in the case of South-East Europe, where, beside a period of strong winds and rainfall (6-13.3.2012), intense precipitation in North-East Greece (Alexandroupoli) were found to be correlated with distinct high energy flux enhancements. A rough theoretical interpretation is discussed for the space – atmospheric extreme weather relationship we found. However, much work should be done to achieve early warning of space weather dependent extreme meteorological events. Such future advances in understanding the relationships between space weather and extreme atmospheric events would improve atmospheric models and help people's safety, health and life.

Keywords: Extreme Weather events, Heat waves, Sun-Earth relationships, Sun and Weather, Space Weather and Extreme Atmospheric events, Global Atmospheric Anomalies, SEP events and Weather, SEP and NAO, Gulf Stream and Heat waves.

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1. Introduction

"A growing mass of evidence suggests that transient events on the Sun affect our weather and long-term variations of the Sun's energy output affect our climate. Solar terrestrial exploration can help establish the physical cause and effect relationships between solar stimuli and terrestrial responses. When these relationships are understood science will have an essential role for weather and climate prediction." This statement was a part of an early proposal of R.D. Chapman submitted to NASA [1]. This statement gains new interest nowadays, since in the past two decades we saw an exceptional number of unprecedented extreme weather events, some causing major human suffering and economic damage [2].

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Since the beginning of the space era, and, in particular, during the last two decades, an amount of evidence has been gathered on links between Solar activity and variations in the Earth's ionosphere and atmosphere.

There are many reports from the beginning of space era suggesting a correlation of solar flares with pressure gradients in the atmosphere, within 2-3 days or less (<6h) [3, 4, 5, 6, 1, 7, 8, 9]. In the last two decades, great emphasis has been given to the solar cycle climate trends of cloudy, stratospheric changes, polar temperatures and winds, as well as the sea and surface temperatures. Most of these meteorological variations have been discussed in terms of solar irradiance as a stimuli, but recently it suggested that energetic particle forcing driving dynamical changes in the atmosphere are as intense as those arising from the solar irradiance variations [10]. In these studies, the solar particles were considered to affect the atmosphere via a slow process of catalytic ozone destruction.

However, the question on the relationship between Solar Energetic Particle events and atmospheric weather variations, in particular, with the extreme ones, is still open.

It is worth noting that the historic March 2012 heat wave was not anticipated by solely atmospheric models. For instance, it has been noted that "A black swan most probably was observed in March 2012". Since, in March 1910, before the GHG era, similar temperatures were recorded with those in March 2012, several scientists agree that the "Meteorological 2012 March Madness" should be explained by physical and not anthropogenic agents. However, no convincing new suggestions have been proposed to explain the March 2012 heat wave in USA and other extreme events over the globe, within the framework of meteorological models, so far.

In a previous study we suggested that solar and magnetospheric particle events are consistent with a cause of the extreme atmospheric weather events all over the globe, and in particular, the historic March 2012 heat wave in East USA/Canada [4]. [4] noted that a great CME (March 7, 2012) and a related geomagnetic superstorm were followed by various extreme phenomena as high temperatures, intense rainfalls and ice extent at middle and high latitudes were recorded all over the globe (USA, Europe, Australia, Antarctic), while unusual measurements of various atmospheric and ionospheric quantities were observed by a series of satellites (TIMED, MODIS, NOAA etc.).

Therefore the question is: What are the primary physical processes that make an event extreme? Is it possible for the Solar Energetic Particle (SEP) to provoke extreme weather events, like heat waves? By which mechanism? Addressing this question is crucial to understanding the causes of extreme events and to assess potential predictability. The answers are important for providing early warning of extreme weather events.

In this paper we extend the case study by [4] to a statistical analysis on the possible relationship of strong SEP events with extreme temperature increases. For this reason we present results from a statistical study based on the selection of the strongest (Dst ≤ −150 nT) interplanetary coronal mass ejections (ICMEs) observed from the beginning of the life of ACE spacecraft in 1997 until May 2015. A comparison of the space and atmospheric events during the times of the selected ICMEs suggests a correlation between the strong ICMEs-related SEP events and temperature increases in north-east USA (Madison, Wisconsin). Other atmospheric extreme phenomena on the globe were also found to counteract the March 2012 heat wave in USA (and other SEP periods examined), but here we only make a short reference to rainfall and strong winds in Greece (during March 2012).

2. Data

In order to check the possible link between the high solar activity and atmospheric extreme events, we selected time periods with SEP events related with strong storms / superstorms. For the selection of very strong geomagnetic storms we demanded geomagnetic Dst index values as low as Dst ≤ −150nT, and we examined the period from the beginning of the ACE mission (1997) until May 2015. Such large (Dst ≤ −150nT) storms are known to be caused by strong ICMEs [11]. By using a catalogue of CMEs [http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm], we found only 28 SEP events meeting the above criterion for large (Dst ≤ −150nT) related geomagnetic storms within about 18 years of ACE records and we made a full analysis for 26 events, due to a data gap of 2 events (Table 1; Events

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#6 & #22, which were put in brackets). It is noted that, agreement with previous results [11] the majority of the large ICME-induced storms were recorded during the maximum phases of solar cycles 23 and 24 (18 out of the total of 28 events).

Then we investigated the possible correlation of the SEP events observed by ACE with various atmospheric parameters (temperature, wind, precipitation), around the times of the CME-related storms. In some cases we checked the status of the atmospheric environment with data from MODIS (Moderate Resolution Imaging Spectroradiometer) instrument onboard the TERRA satellite.

ACE (Advanced Composition Explorer) is a spacecraft (http://www.srl.caltech.edu/ACE/), which has been circulating, around the L_1 Lagrangian point; L_1 is the point of Earth-Sun gravitational equilibrium at a distance of ~220 R_E, from Earth, where R_E is the length of Earth's radius. ACE was launched on August 25, 1997 from the Kennedy Space Center in Florida and has been continuously providing in situ observations until now. The ACE scientific research instrumentation includes eight instruments that measure plasma and energetic particle composition, as well as one to measure the interplanetary magnetic field (Stone et al. 1990) .

When reporting space weather, ACE provides an advance warning (about 1 hour) of geomagnetic storms. Real-time observations with 1 second resolution are provided continuously to Space Environmental Center (SEC) of the National Oceanographic and Atmospheric Association (NOAA). For the present study we used data from the ACE Level 3 Summary Plots (http://www.srl.caltech.edu/ACE/ASC/DATA/level3/summaries.html).In particular, for the needs of our study we used the data from the EPAM (Electron, Proton, and Alpha Monitor) particle instrument (http://sd-www.jhuapl.edu/ACE/EPAM; [http://www.srl.caltech.edu/ACE/ASC/level2/lvl2DATA EPAM.html].

In the next section we provide measurements from the channels P'2 (ions), P8 (ions) DE1 (electrons) from the LEMS120, LEFS150 and LEMS30 telescopes of the EPAM instrument, respectively; the numbers of these telescopes designate the angular orientation in degrees (150, 120 and 30) from the center of each channel with respect to the spacecraft spin axis which is always pointed towards the Sun (Gold 1998). Since the vast majority of the ions measured are protons, we call the ion measurements in the next section "proton" measurements. The three EPAM /ACE channels P'2, P8, and DE1 were chosen in order to compare the atmospheric weather with low energy (~70-115 keV) protons (P2'), high energy (1880-4700 keV) protons (P8) and energetic (~40-50 keV) electrons. The long time (days) structures of the P8 high energy ions are of solar origin; spikes of low energy P2′ protons and DE1 electrons are originated from the Earth' s magnetosphere [13].

Ground data of atmospheric temperature, precipitation and wind direction were obtained from the WeatherOnline site (http://www.weatheronline.co.uk/weather/).

3. Data analysis

The set of 26 time intervals with the largest (Dst ≤ −150nT) CME- induced geomagnetic storms during the time period of ~18 years (1997-2015) was examined in order to compare the SEP events with possible significant weather events. We compared the SEP events observed by the ACE spacecraft with the atmospheric weather at various sites over the globe and the most important conclusions of our investigation were (a) an evidence for significant or even great temperature increases during winter times in North-East USA and (b) a less significant trend for rainfalls and other "winter" weather conditions in Greece. A preliminary investigation of the whole set of 26 SEP events and the weather at various sites of Earth suggests that at least in some cases, as for instance, March 2012, the SEP events were related with global atmospheric weather extremes.

In subsection 3.1 we show representative observations, where three SEP events are compared with the atmospheric weather conditions in Madison, Wisconsin. In subsection 3.2 we present the results from a statistical study on temperature variations in Madison during the 26 large storms. Finally, in subsection 3.3 we provide data and published information for the March 2012 large SEP event and the weather over the globe, including Madison / Wisconsin and Greece.

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In order to provide information for each of the 26 periods examined we show in Table I the date of the onset of the high energy proton P8 and the corresponding temperature in Madison T_i as well as the date T_f when the temperature in Madison takes its maximum value. We also show the time difference $\Delta T = T_f - T_i$, the time period $\Delta\tau$ (in days) between the dates with T_i and T_f, as well as the lowest value of the index D_{st} corresponding to the selected geomagnetic storm.

Table 1. Date of a SEP onset and the corresponding temperature in Madison, maximum temperature in Madison and the corresponding date, temperature increase and its corresponding time duration along with the lowest value of the index Dst of the selected geomagnetic storm

	Year	Month	Day (T_I)	T_I	Day (T_F)	T_F	$\Delta\tau$	ΔT	Dst
1	1998	9	24 (267)	17	26(269)	29.5	2	12.5	-207
2	1998	8	27 (239)	25	29(241)	28.5	2	3.5	-155
3	1998	5	3 (123)	3	4(124)	23	1	20	-205
4	1999	10	17 (290)	9	21(294)	19	4	10	-237
5	1999	9	21 (264)	15	26(269)	28	5	13	-173
[6]	2000	11	9 (314)	2	12(317)	6	3	4	-159
7	2000	10	6 (280)	6	10(284)	17	4	11	-182
8	2000	9	15 (259)	16	18(262)	29	3	13	-201
9	2000	8	5 (218)	22	14 (227)	29	9	7	-235
10	2000	7	12 (194)	26	13 (195)	29	1	3	-301
11	2000	4	4 (95)	7	5 (96)	14	1	7	-288
12	2001	11	20 (324)	6	24 (328)	16	4	10	-221
13	2001	11	5 (309)	14	6 (310)	19	1	5	-292
14	2001	10	25 (298)	3	28 (301)	14	3	11	-157
15	2001	10	16 (289)	9	22 (295)	17	6	8	-187
16	2001	4	15 (105)	1	11 (101)	23	-4	22	-271
17	2001	3	25 (84)	-6	30 (89)	10	5	16	-387
18	2002	10	7 (280)	10	11 (284)	23	4	13	-146
19	2002	9	3 (246)	26	8 (251)	32	5	6	-181
20	2003	11	19 (323)	12	20 (324)	18	1	6	-422
21	2003	10	26 (299)	7	30 (303)	18	4	11	-353
[22]	2004	11	8 (313)	5	10 (315)	17	2	12	-263
23	2004	7	24 (206)	22	27 (209)	28	3	6	-170
24	2005	8	22 (234)	21	27 (239)	29	5	8	-216
25	2005	5	12 (132)	10	22 (142)	25	10	15	-247
26	2006	12	7 (341)	-8	14 (348)	11	7	19	-162
27	2012	3	4 (64)	-2	15(75)	28	11	30	-145
28	2015	3	5 (64)	-9	16(75)	23	11	32	-222

Figure 1 shows time profiles of the daily maximum value of temperature T_M in Madison, Wisconsin (panel a), the direction of the wind in the same town (panel b), the fluxes of energetic (38-53 keV; DE1 channel) electrons, and of both the low (68-115 keV; P1 channel) and the high (1880-4700 keV; P8 channel) energy protons observed by the spacecraft ACE outside the Earth's magnetosphere (panel c) along with the geomagnetic index Dst (panel d), for the time period March 3-31, 2015; the time series of Figure 1 have been centered around the time of the severe (G4) storm of March 17 which was triggered by the most intense CME of the solar cycle 24 (Dst index reached values as low as -223 nT on day 17).

By comparing the profiles of the ACE energetic particle flux profiles (panel c) with the profile of temperature T_M (panel a) we see a gradual increase of both *P8* flux and T_M values from day 6 until day 16 (the day before the CME arrival), and a decrease of both T_M and *P8* from 17 to 28 March, 2015. It is pointed out that the temperature T_M increased from -9^{0}C to 23^{0}C, i.e. a total increase ΔT_M= 32^{0}C, within 10 days (6-16.3.2012) or 3.2°C / day for 10 days. This temperature variation means a change from a winter-type weather (-9°C) to a summer-type one (23°C) in the beginning of March 2015.

From Figure 1, we also see a better correlation of the high energy proton flux than of the low energy proton and electron flux with the temperature T_M (in particular during the arrival times of high energy solar protons between 6-16 March). The short lived spikes of low energy protons are obviously of a terrestrial origin (magnetosphere, bow shock) and their presence is evident throughout the geomagnetic storm, in particular between days 17-25. From these observations we can infer that the long lived and great temperature increase during March 2015 was related with the SEP event and not with the highly activated magnetosphere. An increase of DE1 electron flux was also observed during the maximum of the SEP event, as inferred from the P8 flux-time profile, between days ~15-16.

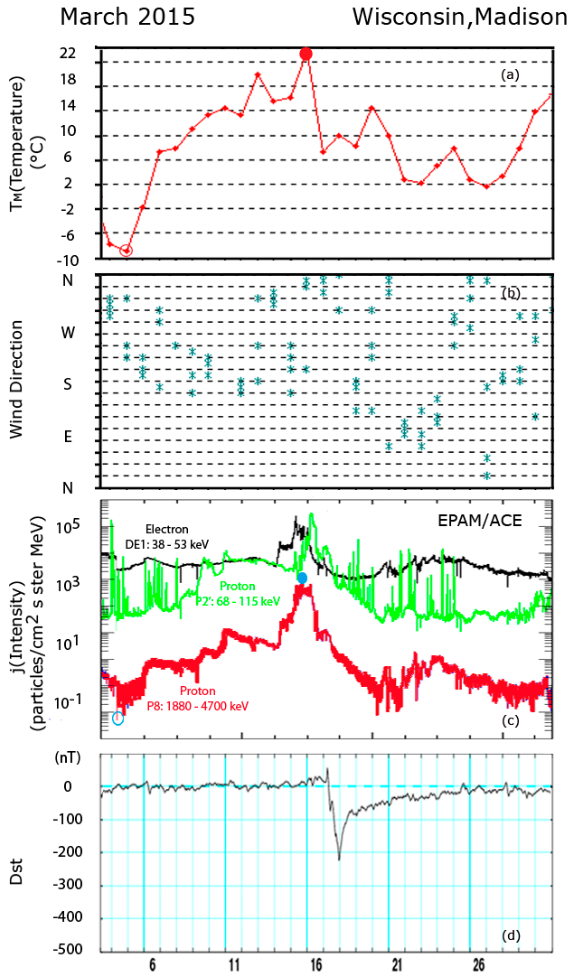

Figure 1: Time profiles of temperature in Madison, Wisconsin (panel a), the direction of wind in the same town (panel b), the fluxes of energetic proton and electrons observed by the ACE spacecraft and (d) the values of the geomagnetic index Dst, during March 3-31, 2015. It is evident that the temperature profile (panel a) resembles that of the high energy solar proton flux P8 (red curves). In particular, we note that the great temperature increase from -9°C to 23°C, between 6-16.3.2015 (panel a), was recorded under a general south wind streaming (panel b).

Further comparison between panels a, b and c demonstrates that during the time of the gradual increase of energetic protons at ACE and the temperature in Madison, the wind shows a general flow from the southward direction (days 6-16; panel b). On the contrary, we see that before day 6 (days 4-5) and after day 16 (days 17-19), both the P8 proton flux and the temperature T_M in Madison show low values, which were accompanied by air flows from northern directions.

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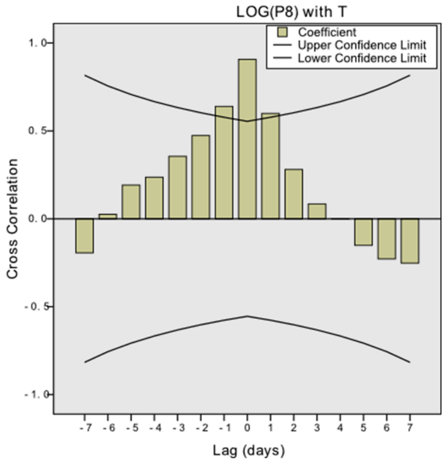

Figure 2: The estimates of the cross-correlation coefficients r for lags k = 0;±1;…;±7, between the daily values of the logarithm of the P8 proton flux values and the temperature T_M from day 6 until day 16, March 2015. The solid black lines present the asymptotic 95% confidence limits of the estimated coefficients. The very large r value at lag=0 confirms and explains the good resemblance of *P8* and T_M curves seen in Figure 1.

In Figure 2 we present the estimates of the cross-correlation coefficients between the logarithm of the P8 proton flux values and the temperature T_M from day 6 until 16 (Fig. 1) and for lags 0, ±1,..., ±7. The upper and lower confidence limits are denoted with solid black lines. We found a very significant positive correlation at lags -1, 0 and 1. Especially at lag = 0 the cross-correlation coefficient takes its maximum value r = 0.907 with s.e.= 0.277(p <0.001). This indicates that one should notice an increase of the temperature T_M from the previous day till one day after an analogous increase of the proton flux. The very large r value, at lag = 0, confirms and explains the day to day simultaneous resemblance of the line plots of the temperature T_M and the P8 proton flux in Figure 1. The significant level of the correlation is better than 0.001, which suggests a very significant correlation between the two magnitudes (T_M and the P8), or between space weather and atmospheric weather in Madison.

The very strong and significant correlation between the temperature in Madison during a time interval of ~10 days before the occurrence of the geomagnetic superstorm suggests that the change of weather in Madison may be causally dependent to the SEP event.

Figures 3 and 4 have been constructed as Figure 1, but at times around the superstorms of December 2006 (Figure 3) and September 2002 (Figure 4).The data set in these two figures show similarities with each other and with the data examined in Fig. 1. The large structures of energetic particle fluxes (panels c) between dates 6-20.12.2006 (Figure 3) and 6-16.2002.2002 (Figure 4) are obviously of solar origin. There are also some differences. In both cases, the solar events show a rather abrupt flux increase in all of the three channels (DE1, P2′, P8) in contrast to the solar event of March 2015 (Figure 1). These profiles suggest a rather good magnetic connection of the ACE / Earth with the corresponding solar source. After the SEP maximum, the DE1, P2′ and P8 fluxes display a gradual decay, with several low energy P2′ proton spikes of a terrestrial origin [13].

The most important common feature of the great CME-SEP events in December 2006 and September 2002 is a significant temperature increase (panel a) during times of highest solar particle fluxes and a general south wind streaming (panel b). However, there is a remarkable difference in the solar events in December 2006 and September 2002. During the “winter” event of December 2006, the temperature T_M climbs from -7^{0}C to 11^{0}C, that is an increase $\Delta T_{M,}$= 19^{0}C, within only 7 days,

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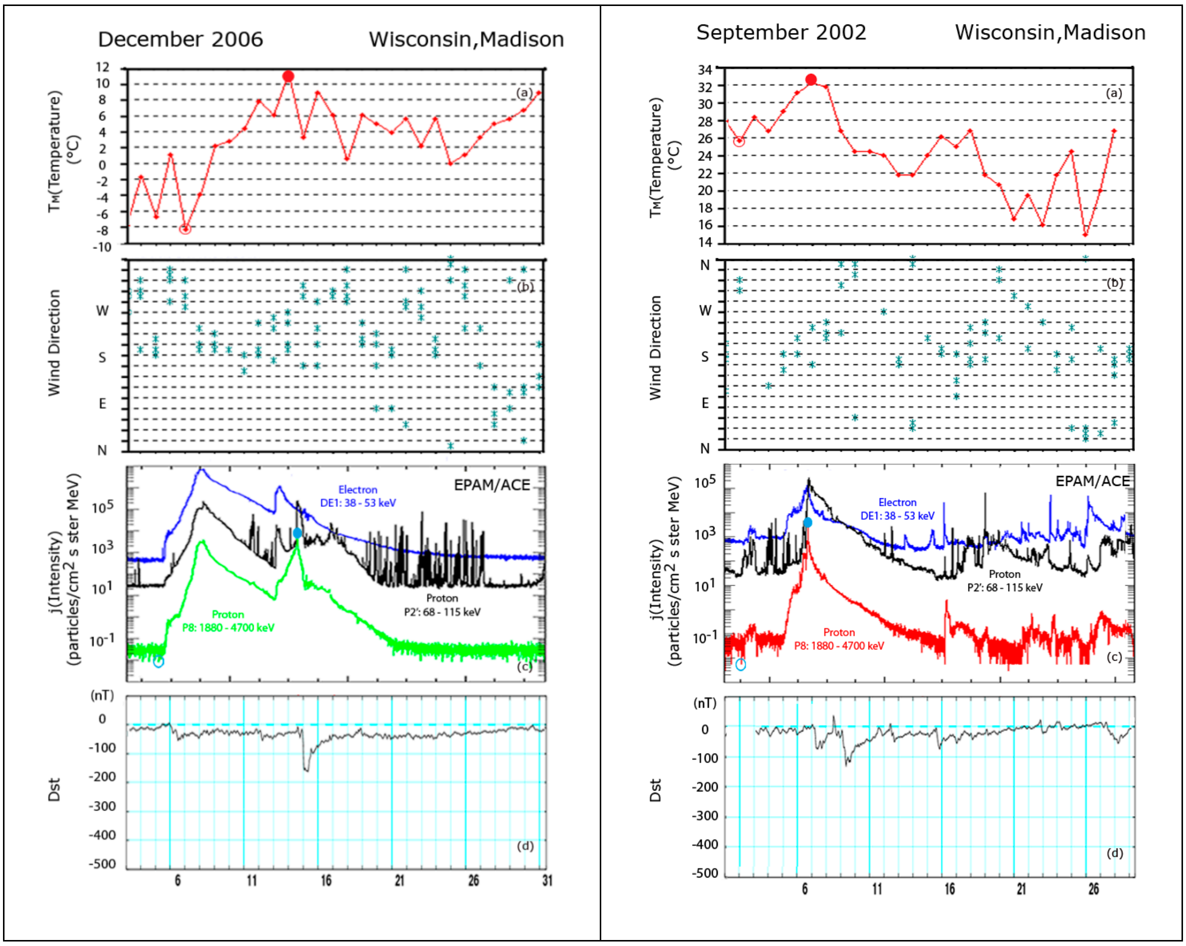

Figure 3. As in Figure 1 but for the SEP events related with the December 2006 (left side) and September 2002 (right side) ICME-induced great storms. The temperature increase T_M in Madison (Wisconsin) was much greater (panel a) in December 2006 ($\Delta T = 19^0$C) than in September 2002 ($\Delta T = 4^0$C) during a south wind, bur under different pre-event temperatures (-8^{0}C versus 4^{0}C).

which resembles the great change from winter to summer weather in Madison in March 2015 (Figure 1). On the contrary, the increase of the temperature T_M was much lower in September 2002, with an increase from 28^{0}C to 32^{0}C, that is a total increase of only 4^{0}C, in the same town, but under a very high pre-event temperature level (~28^{0}C compared to -8^{0}C in December 2006 and -9^{0}C in March 2015). It worth noting that this difference in the T_M variation under a different pre-event temperature level ("summer" –"winter" asymmetry) was found to be a characteristic statistical significant result in the sample of 26 events examined, as we will see in the next subsection 2.3.

In addition, we note that in the cases of SEP events of December 2006 and September 2002 with abrupt flux increases, the T_M temperature does not show such a strong and significant correlation with P8 flux as in the case of gradual flux increase in March 2015. This may suggest that the troposphere follows well the progress of SEP events during a slow external stimuli.

3.2. Statistical Results on temperature increases in Madison, Wisconsin (USA)

Figure 5 shows the distribution number of the 26 SEP events with a time delay $\Delta\tau$ (=T_M - P8) between the day of the maximum temperature T_M in Madison and the day of the maximum solar proton flux P8, within a time interval of 15 days centered on the day of the ICME arrival. Positive (negative) values of delay time $\Delta\tau$ means later (earlier) recording of maximum temperature T_M in Madison than that of the maximum solar flux P8. From Figure 5 we see that the majority of events show non-negative values, which suggest that maximum surface temperature either coincides with ($\Delta\tau = 0$) or follows ($\Delta\tau > 0$) the proton maximum P8.

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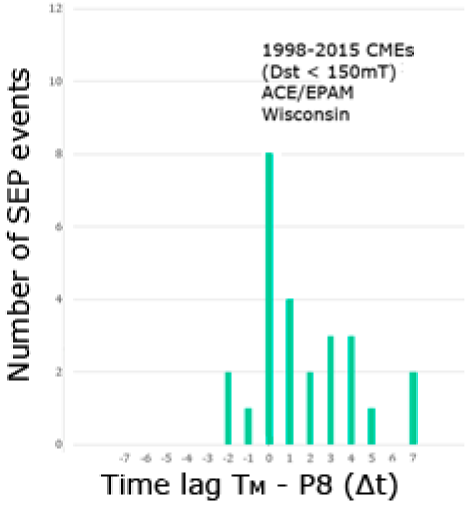

Figure 4: Distribution number of SEP events with time lag Δt between the day of maximum temperature T_M in Madison and the day of maximum high energy solar proton flux P8 during a period of 15 days centered at the day of the ICME (=0 at the horizontal axis). The large number of non-negative values suggests that the maximum temperature T_M coincides with or follows the day of solar proton maximum.

In Figure 5 we present scatter plots of the total temperature increases ΔT_M versus the time duration Δτ of the temperature increase, for winter times (October to April; panel a) and for summer times (May - September; panel b), respectively. Panel a shows a very strong correlation (r = 0.8), between ΔT_M and Δτ, which is very significant (p <0.001). A linear interpolation shows a trend b = 2.026, which suggests an average daily temperature increase $\Delta T_M / \Delta\tau \approx 2^0$C / day at winter time periods in Madison, during the SEP events related with very large (Dst ≤ −150nT) storms. From panel b we infer the absence of a significant correlation between ΔT_M and Δτ during the "summer times". Furthermore, from a comparison of the data in panels a and b, we infer that the SEP events examined are related with lower temperature increases ΔT_M in "summer" times (panel b) than in "winter" times. This finding is a reasonable result for an external stimuli of the atmospheric circulation.

When all of the 26 events are considered (panel c) a significant correlation was also found between ΔT_M - Δτ (r = 0.5, p<0.01).

The statistical results of Figure 4 and 5, that is the occurrence of high temperatures in Madison T_M after the maximum flux of CME-related high energy protons P8 and the very strong and significant correlation between T_M and *P8* during "winter times" suggest that most probably there exists some physical causality between SEP events and atmospheric weather in North-East USA (Madison / Wisconsin).

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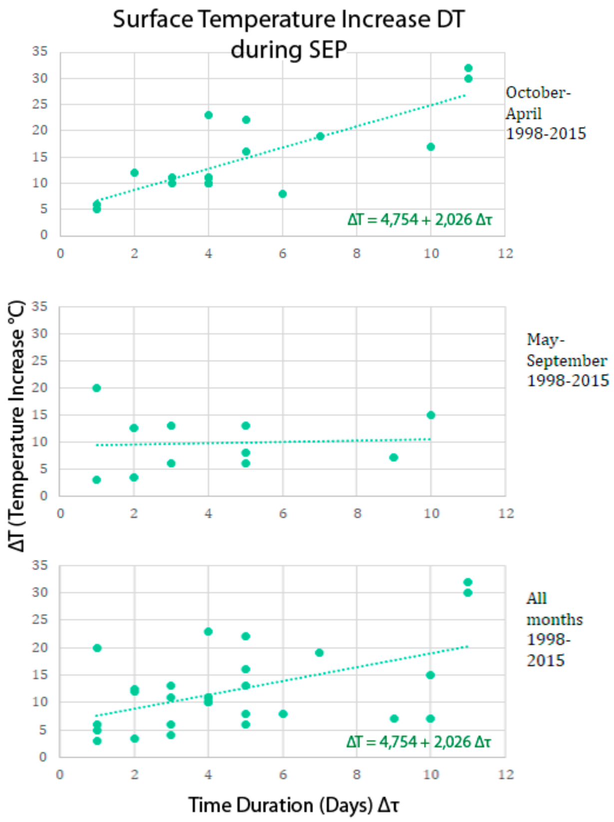

Figure 5: Surface temperature increase ΔT during SEP events as a function of the time duration Δτ of the temperature increase, during “winter” (a) and “summer" times (b). During “winter times", a strong and very significant (r = 0.8; p <0:001) correlation was estimated.

3.4. SEP events and global atmospheric extremes (March 2012)

From the previous analysis of space and meteorological events during times of 26 selected ICME-related SEP events (1997-2015) we inferred a correlation between the strong ICME-related solar energetic (>~2-5 MeV) proton fluxes and the temperature increases in north-east USA (Madison, Wisconsin) during “winter” times. Other atmospheric anomalies were also found to follow the SEP events over the globe, but here we only make a short reference to the extreme weather event in South-East Europe following the March 2012 CME.

Here we concentrate on the comparison of CME-related SEP event observed by ACE with the atmospheric weather extreme in two cases: the north–east USA (Figure 6, left side) and Greece (Figure 6, right side).

Figure 6 has also been constructed as Figure 1. Figure 6-left side compares the EPAM / ACE electron and proton observations with temperature and wind stream direction in Madison / Wisconsin, between 3-30 March 2012, while Figure 6-right side compares the same ACE observations with temperature and precipitation in Alexandroupoli / North Greece, for the same time period.

A SEP structure is obvious in EPAM / ACE data between 4-17.3.2012 and a smaller one between 28-30.3.2012. The flux enhancement on 5th of March is related with the appearance on the solar disk of solar active region (AR) 11429 of the National Oceanic and Atmospheric Administration (NOAA). [14].

The solar flares in March 2012 were analyzed and discussed in extent in the scientific literature [14]. The most intense UV flash of X5-class solar flare occurred on March 7, 2012. This flare was associated with a very intense CME with a speed of ~2000 km s^{-1}.The impact of the 2012 March 7 solar eruptions in the heliosphere and the geospace was striking [15, 16]. Noteworthy is a very strong decrease in cosmic-ray fluxes on the ground, associated with the arrival of the March 2012 ICME [17].

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Furthermore, significant substorm activity was detected in geosynchronous equatorial orbit (GEO) by GOES-13 and 15, in particular on 2012 March 9, during the major geomagnetic storm. [14].

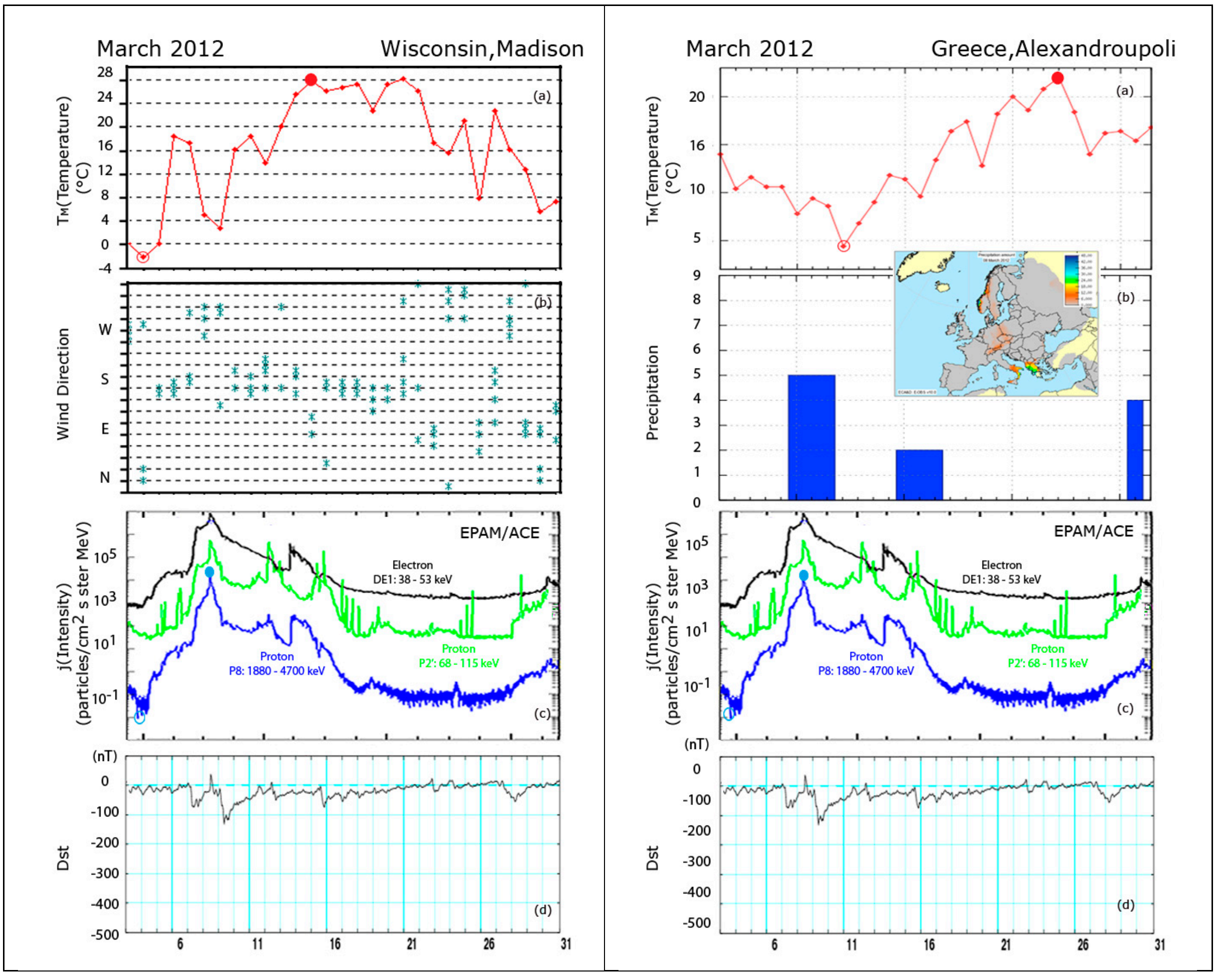

Figure 6. As in Figure 1 but for the SEP events related with the March 2012 ICME-induced great storm, in Madison, Wisconsin (left side) and Alexandroupoli, Greece (right side). The temperature increase T_M in Madison reached an historic maximum, with a change from -2⁰C to 28⁰C, that is $\Delta T_M = 30^0$C, within 10 days (6-16.3.2012), which is not explained by the existing atmospheric models (see in text). Figure 6-right side shows a general anticorrelation between the *P8* high energy proton flux and the temperature in Alexandroupoli / Greece, with three time intervals with rainfall in Alexandroupoli (blue bars in panel b) at times of enhanced levels of high energy proton P8 flux (around days 8, 14, and 30 of March 2012). The inset in the left side shows the precipitation amount evaluated by the MODIS instrument onboard the TERRA satellite on March 8. The different weather in North-East USA and North Greece reflects a global weather anomaly in March 2012 (See Figure 8) during the SEP event.

From Figure 6 we see that there was an increase in the temperature in Madison T_M (panel a) after the arrival of solar energetic particles on 4th of March (panel c), while the wind was streaming from the southward direction (panel b). The temperature T_M, showed a dip for two days (8-9.3.2012), while the wind was streaming from the northward direction, but it continued its gradual increase from day 10 to day 16.

From Figure 6 we see that there was an increase in the temperature in Madison T_M (panel a) after the arrival of solar energetic particles on 4th of March (panel c), while the wind was streaming from the southward direction (panel b). The temperature T_M, showed a dip for two days (8-9.3.2012), while

the wind was streaming from the northward direction, but it continued its gradual increase from day 10 to day 16.

The temperature T_M remained at high levels of ~26-28^0 C for ~7 days, until day 21, under air streams from the southward direction, and then started to decrease; it is pointed out that the T_M increased from -2^{0}C to 28^{0}C, that is ΔT_M = 30^{0}C, within 10 days (6-16.3.2012). This huge temperature variation in Madison reflects a general temperature increase over large regions of North-East America, and is known as an "historic heat wave", which brought the summer in winter times.

On the contrary, in Figure 6-right side we see a general anticorrelation between the *P8* high energy proton flux during the period of the main SEP event (5-20.3.2012) and the temperature in Alexandroupoli / Greece. In addition, three time intervals with rainfall in Alexandroupoli (blue bars in panel b) are seen at times of enhanced levels of high energy proton P8 flux (around days 8, 14, and 30 of March 2012). Actually there existed extreme weather conditions in Greece with strong rainfalls, snowfalls and strong winds… The inset in Figure 8 shows the precipitation amount evaluated by the MODIS instrument onboard the TERRA satellite on March 8, with high values in Greece and Southern Italy; it is remarkable that, at the same time, Western and Central Europe experienced one of the warmest months of March on record [18].

What is of particular interest for the March 2012 events is the detection of very high energy protons from PAMELA (data not shown here). PAMELA is a magnetic spectrometer launched into a near-Earth orbit in June 2006. Among the goals of the high-energy charged particle measurements fulfilled by the PAMELA spectrometer is the observation of particle fluxes enhancements after a sudden energy release at the Sun (SEPs). [19]. PAMELA observed high fluxes of >200 MeV protons between 7-15.3.2012 and even >500 MeV protons between 7-9.3.2012 and 14-15.3.2012 [19, Fig. 1]. Moreover, the increase of >500 MeV proton flux by ~2 orders of magnitude suggest the presence of protons of even higher energies (>>500 MeV). [20] found that an intensification of zonal circulation took place due to the >100 MeV SEP increases, which is able to affect directly the lower atmosphere by changing its thermal state. The incident of >>500 MeV protons in the Earth' atmosphere may produce ionization in the troposphere.

6. Conclusions and Discussions

6.1 Space weather (SEP) and extreme atmospheric weather events between the years 1997 - 2015

The influence of space weather on the Earth's atmospheric weather and climate is an important scientific issue with great social interest. In the past two decades we saw an exceptional number of unprecedented extreme weather events, which caused major human suffering and economic damage. Understanding the causes of extreme weather is of great importance to assess potential predictability and provide early warning.

In the last two decades, great emphasis has been given to long term space (solar cycle) dependent climate changes, but not to possible short time solar effects on atmospheric weather. Significant evidence from early studies (<1990) suggesting a short response of the troposphere to Solar Energetic Particle (SEP) events, has not attracted significant investigation.

In this study we present statistical results from a sample of 26 large ICMEs-induced great (Dst ≤ −150nT) geomagnetic storms between the years 1997 - 2015, which suggest a strong correlation of space weather with the temperature T_M in North-East USA (Madison, Wisconsin).

In particular we found that: (a) during a time period of 15 days (day=-7 to day=+7) centered at the day D_0 of ICMEs arrival at Earth, the temperature (T_M) in Madison shows maximum values, in ~89% of the events examined, not earlier than the day D_0, , (b) the high (P8: 1880 - 4700 keV) energy solar proton fluxes P8 show a much better relation with T_M than the magnetospheric (68-115 keV) ions and)38 - 53 keV electrons), (c) the temperature increase ΔT_M reached is very strongly and significantly correlated with the time duration of the high energy (P8) protons and the corresponding duration $\Delta\tau$

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temperature increase (r = 0.8, p <0.001), (d) the temperature increase ΔT_M during the high energy proton events shows an average rate of ~ 2◦C/day (26 events examined), (e) (d) in some case examined warm air flowing from the southward direction were found to be related with the high energy proton flux and the temperature increase, and (f) the temperature T_M was very strongly and significantly correlated with the P8 proton flux during the gradual P8 SEP increase of March 2015, within ~ 1 day (r = 0.9, p <0.001).

From the above results we infer that the SEP events preceding the great ICME-related 26 great storms, between the years 1997 – 2015, strongly controlled the temperature T_M in eastern USA, in particular, during the "winter" times. A second result implied from several SEP periods we investigated is that the temperature increase in Madison was related with wind streaming from the southward direction.

Among the SEP periods examined between the years 1997 – 2015, one case coincides with the well known March 2012 historic heat wave in North America. During March 2012 the highest temperature in North America was recorded since 1910. NASA has posted an image on "Earth Observatory" entitled "Historic Heat in North America Turns Winter to Summer", which is presented in Figure 7.

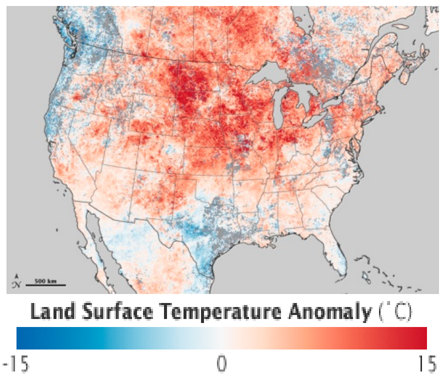

Figure 7. March 8 - 15, 2012 Land Surface Temperature anomaly in North America. (This NASA Earth Observatory image was provided by Jesse Allen, using data from the Level 1 and Atmospheres Active Distribution System (LAADS) and was captioned by Adam Voiland (https://earthobservatory.nasa.gov/images/77465/historic-heat-in-north-america-turns-winter-to-summer).

Moreover, March 2012 was not only a local historic record of warm weather in North America, but a global meteorological anomaly. Various extreme phenomena such as high temperatures, intense rainfalls and ice extent at middle and high latitudes followed the March 7, 2012 CME all over the globe (USA, Europe, Australia, Antarctic), while unusual measurements of various atmospheric and ionospheric quantities were observed by a series of satellites (TIMED, MODIS, NOAA etc.) Selected Weather anomalies all over the globe have been noted by the NOAA "Global Climate Report -March 2012 (https://www.ncdc.noaa.gov/sotc/global/201203); a NOAA map with such anomalies is shown in Figure 8. The National Climatic Data Center (NCDC) preliminary data indicate that March 2012 had a global-mean temperature of 0.46°C above the twentieth-century average [21st].

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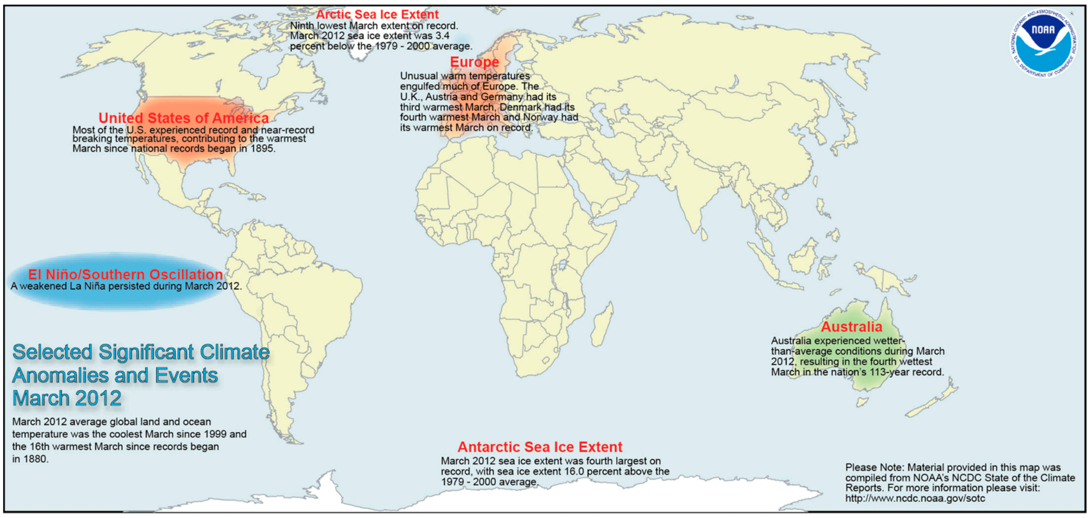

Figure 8. Global Climate Report by NASA for the March 2012 weather anomaly (https://www.ncdc.noaa.gov/sotc/global/201203)

[18] in their study on the origin of the March anomaly state: "Nature's exuberant smashing of high temperature records in March 2012 can only be described as "Meteorological March Madness." The numbers were stunning". This event was not anticipated by solely atmospheric models and it was called a "black swan event" (http://www.esrl.noaa.gov/psd/csi/events/2012/marchheatwave/anticipation.html). [18] also concluded that observations and models are "in rough agreement in suggesting that a temperature increase of up to approximately 1°C could be anticipated from the long-term warming trend, which in the CMIP5 (Coupled Model Intercomparison Project) results is mostly due to external forcing from increasing greenhouse gas concentrations. Compared to the observed peak event magnitude of approximately 20°C, a 1°C increase is small".

6.2 Space weather (SEP) and extreme atmospheric weather event relationship: Physical links?

The March 2012 historic heat waves, several extreme weather events experienced in the past two decades, and the results of the present study pose the question of the possible mechanism(s) mediating certain SEP events with major variations in the troposphere.

Several physical mechanisms have been proposed in order to explain some links between high SEP events and solar magnetosphereric particle activity with changes in atmospheric conditions so far. Such mechanisms include SEP relation with large stratospheric/tropospheric pressure gradient causing downward air flow, variation in the global electric circuits and stratospheric ozone-related chemical energy changes [1, pp. 174-181].

Since our results in the present study indicated a fast correlation between the high energy proton flux and the temperature T_M in Madison (of the order of ~ 1 day; Figure 2), the catalytic ozone destruction, which is a slow process, must not be the major driver of the SEP related temperature variation in north-east USA (Wisconsin).

Furthermore, the results of the present study suggest that the south air flow seems to mediate the influence of SEP events with the surface temperature variations. Furthermore, we note that during the great ICME of March 2015, the temperature T_M increased from -9^{0}C to 23^{0}C (an increase of 32°C), within only 10 days (6-16 March 2015). These results support the concept of a very effective mechanism by which SEP events can produce major tropospheric variations (at least heat waves in North-East America).

The correlation of south wind streaming with the T_M temperature increasing in Madison (and a broad region in North-East America) during SEP events, most probably suggests a physical link between the SEP events- intensification of the warm Gulf stream - T_M temperature increases.

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Although this hypothesis needs further examination, we note the following known physical phenomena, which support such a concept: (1) a correlation between SEP activity and the North Atlantic Oscillation (NAO) [21, pp250-255]., (2) a solar cycle periodicity of the Gulf Stream activity [22], and (3) a correlation between NAO index and the sea surface temperature in the east USA [21]. These results may suggest a physical link between SEP flux increase / NAO index variation / Gulf stream intensification, south warm air flows and temperature increases in east USA. Finally, we note the fast (within ~ 1 day) response of T_M to SEP events, which rather suggests that a non-linear process controls the physical processes described above. Magnetospheric particle may also contribute in weather variations during the large geomagnetic particle activity [10], while hard energy proton (>> 500 MeV) events may trigger global anomalies, as in the case of March 2012.

The present work generalizes the results presented in [23, 24].

In concluding, the 26 Solar Energetic Particle (SEP) events observed by the ACE spacecraft between the years 1997-2015 were found to be related with temperature increase in Madison, Wisconsin, while some of them were related with global weather anomalies (including the March 2012 global anomaly). These results suggest that SEP events should be further investigated as a possible agent of some extreme (global) weather phenomena.

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